Grounding Abstract Concepts Through Robotic Manipulatives

Samantha Speer

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School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213

Thesis Committee:
Illah Nourbakhsh, Chair
Henny Admoni
Kim Baraka

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For my parents and my grandmother who inspire me to do what I love.

Abstract

Technology in education has been on the rise for a long time, developing from computer manipulatives to mobile apps and finally into robotics. Robotics has the unique affordances of the classic physical manipulatives and virtual manipulative, providing both a physical aspect along with computing power for immediate feedback and response. In this work, we aim to explore robotics as a way to combine affordances of pre-existing manipulatives for primary education. Two systems were designed and created: MindfulNest and Owlet. MindfulNest, geared towards teaching children from 3-5 social and emotional development, was tested in a series of classrooms. Owlet, geared at supporting elementary math skills, was also tested in at least one classroom per grade (K-5th). Through these tests, the systems showed potential not only to teach their intended concepts, but also to introduce students to the basics of robotics. The systems and testing also revealed an interesting relationship between the intuitiveness of the devices and the amount that students explored the technology.

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Chapter 1

Introduction

Teaching has always been an area that constantly grows and changes in order to find the best educational practices, especially when it comes to teaching abstract concepts. Teaching skills that involve these abstract concepts can be challenging. Part of this comes from the uncertainty of how people think and process these concepts. Theories have emerged that indicate people may represent all concepts, including abstract concepts, in their brains with concrete images and experience [33]. This idea, known as *grounding* or *grounded cognition*, has been used to understand more how people think and recall. Understanding how people process information also helps people teach that information.

This thesis aims to explore the use of grounded cognition to aid in primary education with regards to abstract concepts. *Physical manipulatives*, objects "that can be handled by an individual in a sensory manner during which conscious and unconscious ... thinking will be fostered" [35], are already being used in education to give students a tangible aspect to what they are learning. With the rise of computers, *virtual manipulatives* were created as a computer version of more traditional manipulatives. Virtual manipulatives have been defined as "interactive, Web based visual representation[s] of a dynamic object that presents opportunities for constructing ... knowledge" [28]. Both kinds of manipulatives provide advantages and disadvantages, fully explored in section 2.4. For example, physical manipulatives provide a tangible aspect for learning, but can be potentially distracting or hard to use. Virtual manipulatives are nearly limitless, but do not provide a tangible aspect for students. This thesis aims to explore a combination of the affordances of both existing kinds of manipulatives through the design and production of different robotic manipulatives.

This thesis explores two primary questions:

1. How can robotic manipulatives be designed such that they combine the affordances of both physical and virtual manipulatives?

2. How pedagogically usable and educationally effective are robotic manipulatives in Pre-K through 5th grade classrooms?

In order to answer the first research question, three systems were created each consisting of a tablet application(s) and robotic manipulative tool(s). We aim to design these robotic manipulative tools such that they have the advantages of both physical and virtual manipulatives. These tools are designed to

1. Provide a tangible interaction for students

2. Provide feedback instantly for students

3. Ground abstract concepts through sensorimotor experiences

4. Require as little setup and entry cost as virtual manipulatives

These three systems were spread across two projects: MindfulNest and Owlet. MindfulNest is a single system designed to help students in Pre-Kindergarten (Pre-K) (ages 3-5) develop social and emotional skills. The second project is Owlet, which consists of the Glow System and the Cube System. Owlet is geared towards helping students in Kindergarten (K) through 5th grade learn math concepts including arithmetic, place value, and fractions. A team of researchers worked on designing and developing each of the systems across the two projects. The MindfulNest system is made up of a single app and three robotic manipulative tools: the flower, the wand, and the squeezer. The Glow System is comprised of a single robotic manipulative, the GlowBoard, and three applications: GlowGrid, GlowPix, and Fractions. Finally, the Cube System is a single robotic manipulative, the CubeTower, and two applications: Cube3 and Cube6. These three systems each underwent pilot testing in numerous classrooms. Each pilot test was preceded by multiple hours of professional development with the tool that was being tested. The studies were observed by a team of researchers and the notes taken during these studies were then analyzed, resulting in a number of design changes and prototype iterations. The findings from these pilot tests also aided in the answering of the second research question.

1.1 Document Outline

This document begins by describing the background research and related work that these projects were built upon (Chapter 2). From here, the motivation for the projects and their approach is described in Chapter 3. The document then outlines the two projects in detail. Chapter 4 explores the design process, development, and testing of the MindfulNest system. It begins with a series of focus groups that lead to the initial development and brief initial testing of the system. From here, the development of the system was continued, accounting for changes in design informed by the initial testing. Once fully developed, the system was tested for a full school year in a Pre-Kindergarten (Pre-K) classroom. The findings for these tests are then stated in Section 4.5.

Chapter 5 details the work done on Owlet. The systems is described, and then the design work during the focus groups is explored. After the initial development, informed by the focus groups, a pilot study was run on the initial robotic manipulative prototypes with one app from each system. The findings are then reported and design changes are detailed in the next section. After more development of both systems, the final two apps from the Glow System were pilot tested with an updated GlowBoard prototype and the findings reported. All findings are then summarized in Chapter 6, and then discussed in Section 6.3. Finally, the document outlines the conclusions drawn from these findings and discusses the future work of the projects, and the questions still remaining to be explored (Chapter 7).

Chapter 2

Background and Related Work

This chapter serves to discuss the background research and related work that provides the theoretical basis for the work done, described in future chapters.

2.1 Grounded Cognition

There has been much research into the topic of how people think, recall, and learn. One theory is that people think not in words or symbols, but in visual images and motor experiences. This theory is referred to as *grounded cognition* [33]. There have been many studies on this topic and the extent to which it applies to different subjects. The most widely accepted models of cognition include reliance on some form of sensory-motor grounding [32]. Building the pathways between sensory-motor experiences and abstract concepts should, theoretically, help people learn abstract concepts. This theory has, in the past, been tested regarding abstract concepts in philosophy, cognitive psychology, and cognitive linguistics. However, there is potential to apply these theories elsewhere, such as math, science, and robotics, to improve learning [4].

Grounding has been applied to many topics, including robotics, to improve understanding of the world around us. Evidence shows a connection between physical actions and emotional words, supporting the idea that grounded cognition exists for emotional states [33]. There is also support for increased learning in STEM classrooms when grounded cognition learning interventions are used [17]. This prior work is what gives us motivation for applying grounding to math education and social and emotional development in this thesis.

2.2 Target Demographics

Social and emotional development begins in children as young as 2 years old [10]. Many Pre-Kindergarten programs have social and emotional development as a main part of their curriculum for this reason [29] [30][14] [13]. Intervening at a young age where student learning focus is on social and emotional development is the best way to reach as many students as possible. This also helps develop good practices from an early age.

Attitudes about math develop early on in a child's education. Studies show that math anxiety has an effect on math ability as early as primary school [21]. This means that intervention at a

young age, specifically in elementary schools, could help students form a better opinion of math and relieve math anxiety.

2.3   Technology Interventions in Primary Education

The use of technology in classrooms has been on the rise since the introduction of computers and other technology. The continued use of technology in the classroom is inevitable, which makes the thoughtful and responsible use of technology imperative. Through the introduction of technology in primary education there has been much critique and skepticism. Early on studies identified barriers for use of technology in education including, but not limited to, teacher attitudes, quality professional development, access to technology, and cost [12]. In order to overcome the cost and access barriers, our testing was done in schools that do not traditionally have open access to much technology, and we developed the systems at affordable price points. Studies have shown that increasing teacher training can shift their attitude towards the use of technology in the classroom to be more positive [6]. Based on this conclusion, we ensured teachers have ample professional development and supporting resources before beginning to use any given system in their classrooms. This helped us to overcome the attitude and training barriers. The study done by Christensen [6] goes beyond just teacher attitudes and further proves that as attitudes increase, the use of the technology increases. This in turn fosters a more positive view of the technology by the students. The more comfortable the students are with technology, the more they will be able to and want to use it.

The use of technology does not stop at just computers. Recently with trends in mobile technology growing, studies have explored the use of mobile technology in the classroom. One study finds that through the use of mobile technology and relevant apps teachers perceive an increase in student learning [9]. However, there are still many criticisms against using mobile technology. Some of these critiques include the ubiquity of the devices, the strict use of the devices, and professional development [37]. Despite these critiques, technology trends in education have pushed even further to robotics. Studies have explored different methods of using robotics in the classroom and integrating robotics into curricula for STEM education [2]. Scratch and other tools for programming and robotics education have also risen in popularity in primary education [31]. Robotics kits, such as LEGO Mindstorms, also gained popularity in the classroom [25]. However, robotics when used in the classroom tends to only focus on the teaching of robotics concepts[20]. The trend of technology in the classroom continues to grow and develop since it first started with computers, and we contribute to it with the development of new robotic tools designed for use in many subjects. It is important to use technology for responsible education that can help students better learn all subjects, including learning about technology itself. In this thesis, the responsible and effective use of technology is considered at each step from consulting experts to training teachers to support student learning.

2.4 Digital and Physical Manipulatives

Physical manipulatives have been around for a long time and endorsed by researchers as having benefits for learning. McNeil and Jarvin endorse physical manipulatives as " [providing] students with an additional resource to use in learning" [26]. They also state that manipulatives can help students draw upon practical, real-world knowledge and introduce physical action which has been shown to help memory and understanding [26]. Manches states two broad categories for the benefits of physical manipulatives: offloading cognition and providing conceptual metaphors [23]. With regards to offloading cognition, manipulatives provide perceptual information like size, color, and shape that can have symbolic meaning to support learning. They also provide a sensorimotor experience for students that helps students offload some tasks. Offloading some tasks allows for students to complete problems they might not be able to otherwise, allowing them to explore more challenging problems. Manipulative can also act as conceptual metaphors, providing a metaphor for students to reason about concepts symbolically and ground new concepts.

However, physical manipulatives have some limitations. McNeil and Jarvin [26] also list some downsides to manipulatives. Manipulatives can be hard to use successfully in the classroom, possibly distracting rather than engaging the students. There can also be problems with the way that manipulatives have a dual representation. Certain manipulative designs can have non-transparent mappings between them and the concepts they symbolize. Physical manipulatives can also take up limited cognitive resources without giving benefit to the students. Additionally, if a manipulative contains extraneous detail, it could distract the students from learning by encouraging them to focus on irrelevant details [19]. Physical manipulatives can also lack immediate feedback about students actions and use, possibly perpetuating misinformation. Virtual manipulatives have been created as a way to circumvent this particular disadvantage.

Virtual manipulatives provide certain advantages in classrooms. Drumus and Karakirik list numerous advantages including immediate feedback provided by the manipulatives to correct the students' actions [11]. Virtual manipulatives also have no physical constraints, new pieces can be easily generated [11][27]. Since virtual manipulatives are online and often available for free, they are inherently more accessible from homes and schools with internet access [11][27]. Moyer also lists the advantage of negligible set-up and clean-up time as they don't require getting out multiple physical pieces and setting them up [27].

Among all these advantages, there also lie some disadvantages. For instance, making manipulatives virtual takes away the hands-on aspect and takes away the connection students make to the mathematical concepts through physical manipulation of objects [18]. Hunt et al. also explore that virtual manipulatives might be better suited for students to practice with rather than learn with, taking away the potential to make connections during learning. There also exists a balance between trying to make the manipulatives easier to use and manipulate and making it too easy to the extent it solves the problems for the student. Like physical manipulatives, virtual manipulatives can fall into design pitfalls and must be designed carefully in order to successfully support student learning.

Chapter 3

Motivation

This chapter explains the motivation for the projects themselves and the research process used to develop MindfulNest and Owlet.

3.1 Technology In the Classroom

Through work with a middle school technology intervention study done by members of the research team, it was concluded that students form opinions about technology from a very early age [8]. The research team thus aimed to implement technology earlier in the classroom in order to develop a sense, plan, act way of thinking from an early age. We hypothesize that this will improve the student's opinions of technology and create a positive idea for the uses of technology within and outside the classroom.

3.1.1 MindfulNest

MindfulNest aims to introduce students to technology in a positive way. During the initial idealization stage, teachers requested technology that helped with social and emotional development as it was a main part of the Pre-K curriculum. The full process is discussed in Section 4.1. Through the use of technology in the classroom we hoped that students would develop not only social and emotional skills but connections between the physical devices, the app, and themselves.

There exists a very negative idea of screen time in Pre-K classrooms [36]. However, the National Association for the Education of Young Children stated that there are two kinds of screen time when it comes to young children: non-interactive and interactive [15]. The non-interactive screen time consists of children watching videos or looking at screens without an interactive component. This can lead to sedentary behavior and does not engage the children nor help them learn. Children learn through interaction with the world, which makes the interactive screen time much preferable over its non-interactive counterpart. Through the use of tangible devices and interactive apps, we refocus the attention of the student from the screen to themselves. We hope that this will decrease the negative stigma around screen time in Pre-K classrooms.

The use of these tangible devices also allows students to have a concrete representation of emotions and coping skills. This helps them learn different standards in Pre-K curricula like 16.1 PK.A, which states that students should be able to "distinguish between emotions and identify socially accepted ways to express them." [29]. Not only do students have a way to express and cope with their emotions, but teachers have another set of vocabulary to discuss these emotions with the students. Integrating technology into the classroom also helps with technology standards such as those in the Pennsylvania standards centered around computer and information technology [29].

MindfulNest was designed based on guidelines for proper and thoughtful use of technology in classrooms. Lyons and Tredwell suggest there are five steps to implementing technology well in the classroom: "(a) assessing technology knowledge of young children, (b) developing technology rules with young children, (c) applying professional judgment and program policy, (d) implementing technology into the curriculum, and (e) collecting data for decision making" [22]. We focus mostly on assessing the children's use and knowledge of technology in our initial short term pilots discussed in section 4.3. We focus on the last four steps in our long term pilots discussed in section 4.5, observing how teachers use the technology and what does and does not work.

3.1.2   Owlet

There have been a variety of studies that explore the use of robotics in the classroom to support the learning of math concepts [5]. Studies show that it is possible to map common core standards for mathematics to robotic tasks as a way to use robotics to teach mathematics in middle school classrooms [1]. This and other studies focus on the pure integration of robotics into middle school math classrooms. We aimed to take this research further by going into elementary classrooms to reach students before they have formed negative ideas of their abilities to do robotics or mathematics. We also aim to create a tool that might improve mathematics education by helping to correct misconceptions while also integrating technology into the curriculum.

Martin [24] describes a theory on the use of physically distributed learning for learning new math concepts. This theory uses a form of co-evolution between actions and ideas. The actions of students are done through the use of manipulatives that influence the ideas of the new mathematical concepts that in term inform the manipulative use and so on. We expand on typical manipulative use and involve both the actions (use of the tangible tool) and ideas (problems and challenges presented through the app). They support and influence each other in a cycle, as shown in Figure 3.1. A specific example of what this cycle might look like for Owlet (GlowGrid Addition: Explore, section 5.1.2) is shown in 3.2, where the app shows an equation with colored numbers, encouraging students to turn dials of those colors.
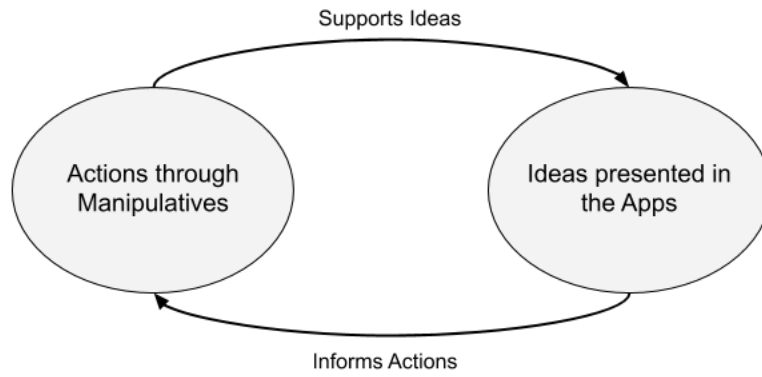
Figure 3.1: Flow chart describing the cycle of actions and ideas.
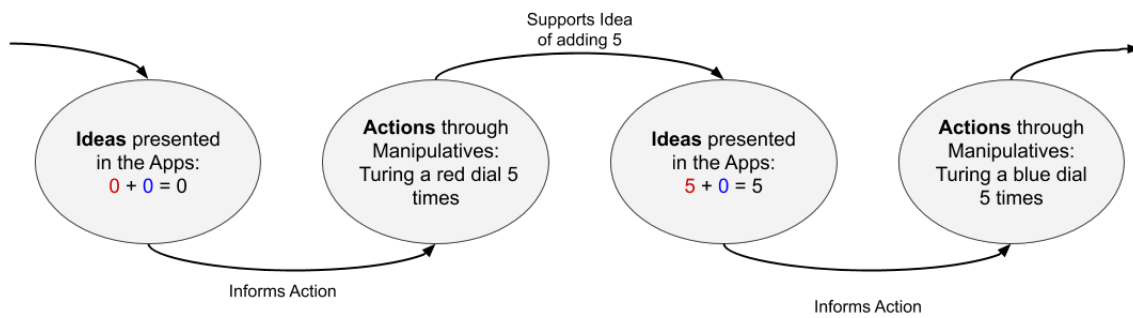
Figure 3.2: Example of the action/idea cycle from GlowGrid using the GlowBoard.

Chapter 4

MindfulNest

MindfulNest is a tool to be used in Pre-K classrooms to help students from ages 3 to 5 develop social and emotional skills. It consists of a set of physical manipulative devices instrumented with sensors and Bluetooth capability and an Android app deployed on an Amazon Kindle. There are three different manipulative devices in MindfulNest: the flower, the wand, and the squeezer. We developed MindfulNest over the course of two years through focus groups, development periods, and pilot studies with continued development and updating throughout. The focus groups were primarily used to develop the initial ideas for physical devices that would be engaging and help ground the coping skills children use to calm themselves down. We then developed an initial prototype to be deployed in Pre-K classrooms, shown in Figure 4.1. The initial pilots gave great insight into how teachers wanted to use MindfulNest in the classroom and how students interacted with the tool. We used these initial tests as a means to gauge what worked for students and what did not. From these pilots, the tool was updated and redesigned to fix issues then piloted for a year in two different Pre-K classrooms. The main focus of the second pilot test was seeing how the completed system performed and what further changes would make it more useful.

4.1 Focus Groups

MindfulNest began as an idea based on the continuation of tangible interfaces for grounding abstract concepts. The first idea of the tool was meant as a way to introduce students to technology and its basic principles. We then recruited 6 pre-kindergarten and kindergarten teachers for a series of focus groups focusing on brainstorming, paper prototypes, and digital prototypes. The first brainstorming session revealed the problem space that the teachers most wanted the technology to fit into: social and emotional development. We then asked the participants to brainstorm the types of interactions they wanted to see, and the educational goals they have for their students as well as possible ways technology could aid them in achieving those goals.

We created paper and digital prototypes based on the initial ideas from the brainstorming process. The focus group sessions where these were explored, focused on how a child would interact with the app and the physical devices, and what skills the project would support. This process yielded the initial set of coping skills in the app, including those three that corresponded to the three robotic manipulatives: the flower, wand, and squeezer.

Figure 4.1: The initial version of MindfulNest

4.2 Development Process

MindfulNest began development from the focus groups with three manipulative devices and their accompanying activities and 6 additional coping skill activities in mind. The first to be developed was the flower manipulative. The first initial MindfulNest pilot began with only the flower and the standalone activities. During this pilot, the squeezer was added as an activity without utilizing the sensing capability of the device, as this was not fully developed yet. The second initial pilot began with this version of the squeeze activity and device, the flower, and the other standalone activities. Data to develop an algorithm to determine the speed of the wand was collected from students during this pilot, but the wand activity was not available during normal use of MindfulNest.

The tool then underwent a large development period which included many redesigns and updates informed by findings from the first two initial tests. This update included new versions of all three manipulative devices, the stand for the tools, and a new version of the MindfulNest app. This version of MindfulNest was then used in the beginning of the long pilot tests in both classrooms. Throughout this pilot, many findings lead us to change the app and the squeezer. The initial versions of the app, all activities, and initial and final versions of the manipulatives are described below.

4.2.1 Application

The initial flow of the application, shown in Figure 4.3 began with the student selecting their picture from the list of students in the class. They would then be asked "How are you feeling?" and based on the emotion they selected, they would be presented with a set of activities they could try (Figure 4.2). Each activity walks the student through completion with a narrative voice and text instructions on the screen. Once done with the activity they selected, the student would

(a) Emotion selection screen

(b) Mad screen

(c) Sad screen

(d) Happy screen
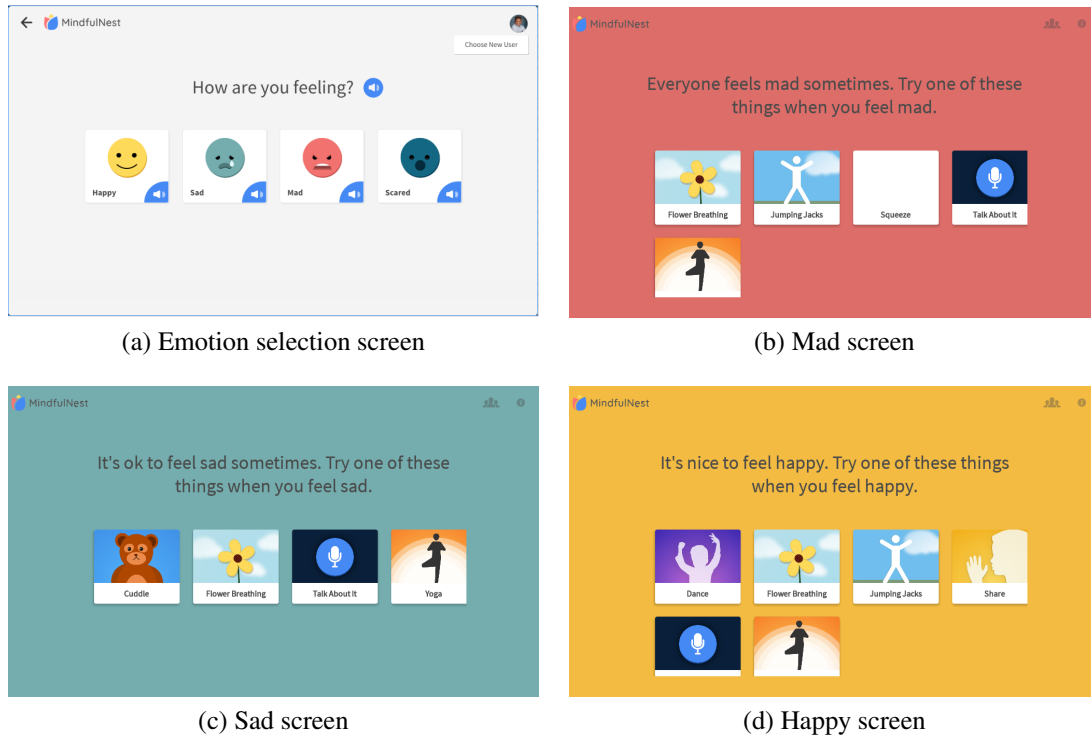
Figure 4.2: The initial emotion screens and the emotion selection screen.

then be asked how fast their heart was beating. Once they answered, the student would be asked how they were feeling after completing the activity. They would then be given the option to use words and record how they felt. After completing this, or after selecting how they felt if they chose not to record, students would be asked if they were ready to rejoin their friends. If they selected yes, the app would return to the student selection screen. If they responded no, the app would take them back to the emotion screen and let them select another activity.

4.2.2 Activities

The activities available in MindfulNest are described in Table 4.1.

A sample screen from each of the activities is included in Figure 4.4

4.2.3 Manipulatives

Flower

The flower manipulative is a digital tangible device that is designed to accompany the flower breathing activity in the app. It is a 3D printed case in the shape of a flower with a microprocessor stationed in the stem. There is a cone in the center of the flower that funnels the student's breath into a microphone. This microphone then detects when a student is breathing on the device and lights up a ring of LEDs. The LEDs change colors with every new breath, changing from white

13
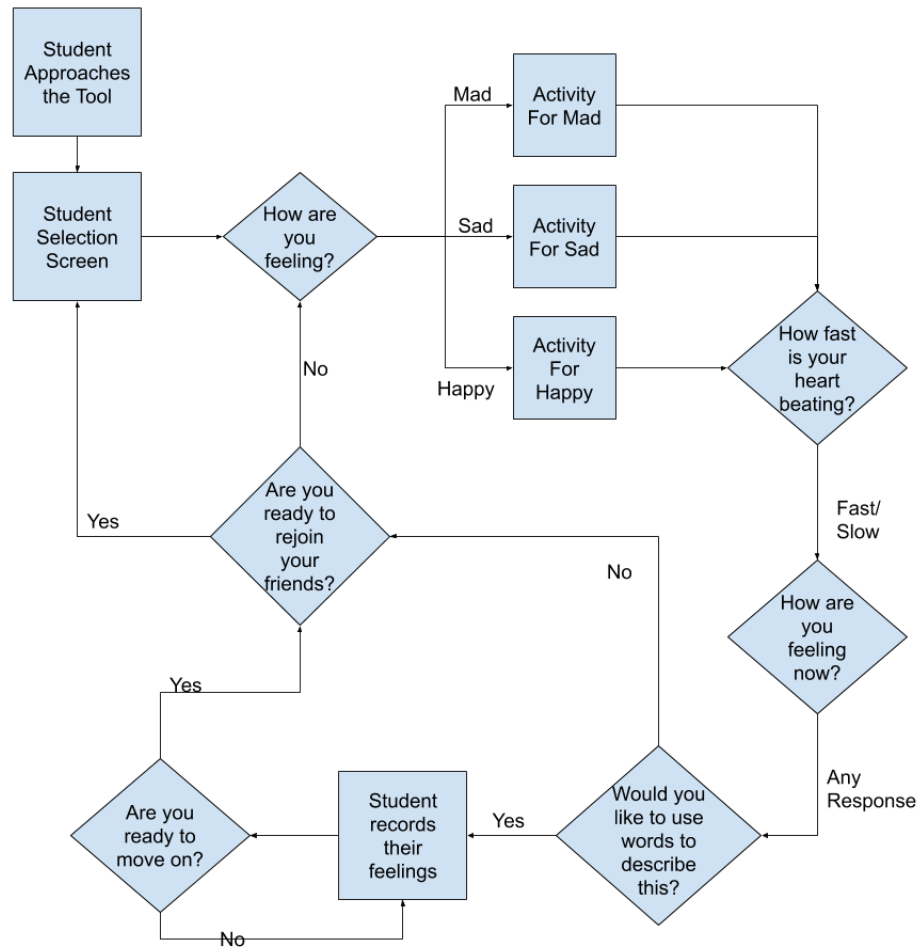
Figure 4.3: The initial flow of the MindfulNest app.

to colored progressively along the ring clockwise. When the student breathes in again, the lights turn back to white in a counterclockwise direction.

Wand

The wand manipulative is a robotic manipulative that accompanies the wand activity in the app. It has a 3D printed case covering a microprocessor and IMU, with an LED at the tip. The IMU detects the motion of the wand and an algorithm classifies it as fast, slow, or stationary. Fast motion causes the LED on the end to light up red. Slow motion causes the LED in the tip of the wand to light up green. The wand also includes a button that lets the student change the color from green. When the wand is stationary, the LED at the end turns white.

(a) Flower Breathing (b) Wand (c) Balloon

(d) Stretching (e) Cuddle a Toy (f) Share With a Friend

(g) Jumping Jacks (h) Dance (i) Talk With Your Teacher
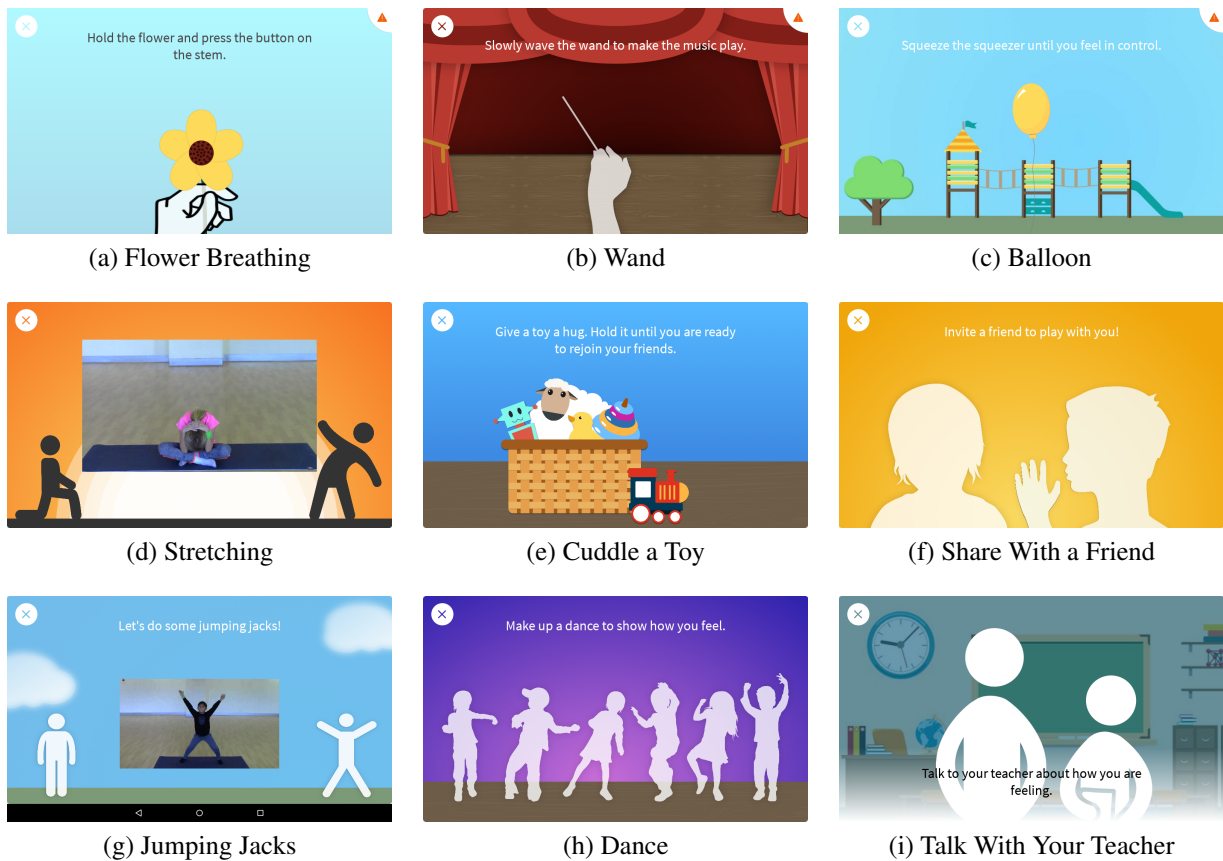
Figure 4.4: MindfulNest Activities. The top row of activities uses manipulatives and will show a warning when the manipulative is not connected. The bottom two rows do not use MindfulNest manipulatives.

Activity Name	Activity Manipulative	Activity Description
Flower Breathing	Flower	The student is asked to push the button on the flower to start the activity. They are then asked to smell the flower and breath on the flower three times.
Wand	Wand	The student is asked to wave the wand slowly to make the music play. When they wave the wand slowly music plays and the wand turns green. When they wave the wand fast, the music goes low and the light on the wand turns red.
Balloon	Squeezer	The student squeezes the squeezer to make the balloon float higher in the air.
Stretching	None	The students are guided through different stretches, depending on which they select.
Cuddle a Toy	None	The student is encouraged to cuddle a toy until they feel better.
Share With a Friend	None	The student is asked to share their emotions with one of their friends.
Jumping Jacks	None	The student is guided through doing jumping jacks.
Dance	None	The student is asked to make up a dance to show how they feel, and background dance music plays.
Talk With Your Teacher	None	The student is encouraged to talk with their teacher about how they feel.

Table 4.1: Description of the activities available in the MindfulNest App.

Squeezer

The squeezer is a robotic manipulative designed to sense when a student applies pressure onto the device. The initial version was filled with beads and relied on air pressure to determine when students squeezed the device. The second version of this manipulative was created out of stuffed fish and turtle toys. The toy included a box with springs that when depressed would allow electrical contacts to touch and indicate the toy was being squeezed.

4.3 Initial Short Term Pilot Tests

4.3.1 System

The app tested in these two pilots began with three possible emotions, all the standalone activities, and the flower breathing activity. Students would first select their emotion, then be presented with different activities depending on the emotion they selected. After completing their activity, students would be asked to place their hand on their heart and say how fast their heart is beating. They could then optionally talk about how they were feeling. Finally, they would be asked how

they were feeling after the activity and if they wanted more time.

The stretching activities included a wristband for the child to put on before starting the activity. This wrist band was initially intended to track their movement and provide feedback on how they were doing. However, the wristband was not yet implemented for the first short term tests, but the cloth band was included with the set.

4.3.2 Research Methods

There were two short term pilot tests done sequentially. The first started in January, the second began in March. Each pilot lasted eight weeks and the teachers were interviewed one week after the end of the pilot test. Both were conducted in Pre-K classrooms in urban neighborhoods in Pittsburgh and served primarily low and moderate income families. There were 9 students (2 boys, 7 girls) in the first pre-k classroom between the ages of 4 and 5, along with one teacher and one aide. The second classroom had 11 students (4 boys, 7 girls) between the ages of 3 and 5 with one teacher and one aide. Teachers participated in four hours of professional development before each pilot began. During this professional development teachers became familiar with MindfulNest, brainstormed ways to integrate the tool into their classroom, and discussed strategies for successful use of the tool.

Over the course of the eight-week pilots, researchers observed for two to three hours once a week. At least one researcher visited the classroom each week. Each week, researchers would speak with the teachers about the use of the tool in the past week since the last observation. Observations were recorded as semi-structured field notes by the researchers. Researchers would observe behaviors of the students when they were feeling extreme emotion and observe if the tool helped them, did not help them, or was not used. Researchers aimed to answer the following questions during the pilots.

1. How was MindfulNest used in the classroom by teachers?

2. How was MindfulNest used in the classroom by students?

After observations we collected all notes and coded them.

4.3.3 Findings

During the first short term pilot, we collected notes and coded them into different categories. The most significant of these were *Student Behavior Outside the App*, *Students Successfully Using the Tool*, *Students Unsuccessfully Using the Tool*, and *Student Interaction with Tangible Devices*. These topics are described in Table 4.2 with examples of notes in each topic. We also had codes relating to hardware and software bugs that were fixed throughout the pilots. These notes were dealt with and fixed and usually did not disturb the students' use as there were two MindfulNest sets in each classroom. The notes regarding the student's behavior outside the app highlighted when they usually had more energy, or triggers in the classroom for overly emotional episodes from the students. This allowed us to understand when the students would need the tool more, and what caused periods of increased use.

Regarding students' successfully using the tool, we noted the students were able to use the app, follow through the whole flow, and afterward be calmer. There were many notable instances

Topic	Description	Example Notes		
Student Behavior Outside the App	This topic was used as an umbrella for all notes regarding how the students were behaving in the classroom when not using MindfulNest.	"Teacher says the kids have a tendency to act out when new people are around"	"When asked what they do to relax one student got up and started doing jumping jacks"	"Student had a lot of energy and didn't know how to channel it. Probably caused by the excitement of the snow"
Student Successfully Using the Tool	This topic contains all notes for a student successfully using the app with regards to the UI, the tablet itself, and calming themselves down with MindfulNest.	"Two students seemed to be more calm when they were in the act of using the flower and clicking through the app"	"Thumbs up is clear as the affirmative to students"	"When the question "Are you ready to rejoin your friends" was asked one student looked over to her friends, thought, then selected her answer"
Student Unsuccessfully Using the Tool	This topic umbrellas all times when students could not use the app's UI, the tablet, or could not calm themselves down with MindfulNest.	" "Talk to your teacher about how you feel" only a couple students (2/16) have done this. Others just go to their seats."	"Students have slight problems with keeping the button on the flower pressed"	"Problems with recording, students press yes but don't record"
Student Interaction with Tangible Devices	This topic is used to organize all notes where the student interacted with the tangible devices.	"Students seem to reach for the flower no matter what"	"Student collected the wrist bands to have both"	"One of the younger students took the flower and banged it against the tablet"

Table 4.2: Note coding topics, descriptions, and examples for initial MindfulNest test findings.

where students enjoyed using the app and reacted as was expected. At some point every student was able to use the app and complete all answers to the followup questions. Students were even able to use the app when they were in states of distress, as shown in Figure 4.5. There were also many instances where students were not quite as successful using the tool. Some were small such as students having trouble holding the button down on the stem of the flower. Others were larger, like the students not putting their hands on their hearts, or walking away after finishing the activity and not following the full flow. The last category was the student interaction with the

tangible devices. We noted that students often reached for the flower before they interacted with the device. They connected their emotions and the activity they were going to do. Another thing we noticed was the students collecting the wrist bands. We hypothesize the students were not connecting the wristband with the activities they were doing and merely wanted to collect them.

Figure 4.5: An upset student using MindfulNest to calm down during initial pilot testing.

Both of the pilots started with an introduction of the tool by the teacher as shown in Figure 4.6. During the second pilot we noted the same four categories of notes along with *student reactions* and *parent involvement*, described with examples in Table 4.3. Again, we had notable interactions with the students and the tool where they used the full flow and were able to calm down while using the tool. We also noted that students in the classroom were a bit younger than those in the other classroom. We noted that these younger students did not know how to use the tablets, and had to be taught this skill. The younger students also tended to not use the coping skill activities as planned. We also noted in general that students had a tendency to occasionally walk away from the tablets before the full flow of the tool was over. The students had positive reactions to the tablet, wanting to take it over to their quiet area to use. When not in the quiet area, they like to use it in pairs and share their feelings. We also noted that parents were involved asking the students to check-in with the tool each morning and telling them to use it. Additionally, we noted that when students interacted with the squeezer, they expected it to do something and interact with the app, like the flower does.

4.4 Continued Development

Based on the observations made during our first set of testing we made some very important changes to the system. We realized the button on the flower was too small for kids to press and increased the size. We also had to increase the sensitivity of the microphone used to sense the breathing. Additionally, the cone that funneled the breath was redesigned to capture more breath from a wider angle. The wristband was removed from the system as we saw students misusing it

Figure 4.6: A teacher guiding the use of MindfulNest in the initial pilot.

Topic	Description	Example Notes		
Student reactions	This code involves direct reactions from the student regarding MindfulNest.	"Students wanted us to see them use MindfulNest when we came into the room. Both choose the flower first"	"Students talk out loud when they use it to check in. Are they responding to the voice like it can hear them?"	"Student wanted to check in multiple times"
Parent Involvement	This topic covers notes regarding the parents being involved with the students' use of MindfulNest.	"Student was checking in and parent encouraged student to use and talk to the teacher"	"Parent encouraged student to check in"	"Parent knew to direct the student to check-in"

Table 4.3: Note coding topics, descriptions, and examples for the second initial MindfulNest test findings.

and no longer believed it would add to the system. We had no way of making feedback from the wristband transparent enough for young students to understand the sense, plan, and act model that the other manipulatives were following.

During the development period between the two pilots, the other two manipulatives were developed. The wand was tested at the end of the second pilot in order to see how students would move it and if they would recognize the change of color of the LEDs. The IMU used in the wand was not sensitive enough to be used to give feedback instantaneously enough for students to understand the feedback. The IMU was changed and the algorithm was redesigned to

better categorize students' movement. The squeezer algorithm and integration with the app was finalized and implemented for the year-long tests. The squeezer was available towards the end of the first short pilot and throughout the second short pilot as purely a physical item. Students and teachers all wanted there to be similar interaction with the squeezer as existed already with the flower. This confirmed the initial design and we then incorporated it into the sense, plan, act model of interaction.

The flow of the app changed slightly after these pilots as we noted that students would become disengaged after the main coping skill activity and walk away during the other activities. We had less post-coping-skill activities and tried to make them more interactive so students would be more engaged. We also added another emotion for the students to select, "scared", in order to broaden the scope of emotions supported by the app.

4.5   Long Term Pilot Tests

4.5.1   System

The system included the changes detailed in the above section. This resulted in the full systems as laid out in Section 4.6. This includes all nine activities: Flower breathing, Wand, Balloon, Stretching, Cuddle a Toy, Share with a Friend, Talk with the Teacher, Jumping Jacks, and Dance; each guiding students through the completion of the activity. It also included the three manipulative devices: The Flower, The Wand, and The Squeezer. The squeezer proved hard to squeeze during the pilot and changed designs completely to become a stuffed sea creature implemented with Bluetooth and springs to sense squeezing.

4.5.2   Research Methods

The year-long pilots were run simultaneously in two classrooms in the same child development center. The center is located in an urban neighborhood and serves primarily low and moderate income families. Each of the classrooms had one teacher and one aide. Total, there were 29 students (14 girls, 15 boys). Students ranged from the ages of 3 to 5. The pilots ran from the beginning of the school year (October) to the end of the school year (March). Researchers observed each classroom once a week for two to three hours. For the first three months two researchers observed each classroom; for the last three months one researcher observed one classroom and two researchers observed the other.

Observations were recorded as semi-structured field notes by the researchers. Researchers would observe behaviors of the students when they were feeling extreme emotion and observe if the tool helped them, did not help them, or was not used. Researchers aimed to answer the following questions during the pilots.

1. How was MindfulNest used in the classroom by teachers?

2. How was MindfulNest used in the classroom by students?

3. Did MindfulNest help students when they felt extreme emotion?

After observations, notes were collected and analyzed into four case studies of the students. These cases studies were of four student groups: Group 1 (age 3), Group 2 (age 3, turned 4

during the pilot), Group 3 (age 4), Group 4(age 4, turned 5 during the pilot, or age 5 throughout). These groups include students of each age from both classrooms.

4.5.3 Findings

The notes collected from the two pilots were broken into categories based on the student they described, general classroom attitudes, and the teacher's guidance of the tool. These categories are described in Table 4.4 along with examples for each. When the tool was first introduced to the students, they were very excited to explore it and use it. However, all students were attempting to play with the tool at once resulting in a very chaotic morning. They eventually began using the tool more as it was intended and less as a toy. While it was new in the classroom, students were more excited about it as a toy. Once they were more familiar with it and the novelty wore off, they began to use it only when they were feeling extreme emotion. We observed students often clicked multiple times in the app while using it, selecting their responses accidentally without actually responding to the prompts.

Category	Description	Example Notes		
General Classroom Attitudes	This topic includes notes regarding most or all of the students in the classroom and how the teachers generally ran the rooms.	"Students like the activities but usually skip the heart beating"	"Students tend to click multiple times for a single selection screen."	"Class in general was way too energetic to focus on any MindfulNest stuff. It was snowing today"
Teacher Guidance of the Tool	This note includes instances where the teachers guided the students to use MindfulNest.	"Teacher calls it a tool, says we're using them not playing with them"	"Teacher used the timer to give someone else a turn on MindfulNest"	"When with the teachers they do all the activities, including heart, without much prompting"
Group 1	This topic includes notes for all students who began and ended the school year at 3 years old.	"[Student] has a hard time doing the flower, he always blows. He pretty much just wants to make it light up"	"[Student] has the wrong wand, but he doesn't care and waves the wrong one anyway"	"[Two students] threw the manipulatives around and didn't put them back in the stand"
Group 2	This topic includes notes for all students who began the school year at 3 years old and ended it at 4 years old.	"[Student] was upset and just wiggled around on the ground instead of doing anything. She would click the activities and just look at them	"[A Student] is trying to use it while another student takes other manipulatives from the stand. [The first] student is still able to calmly wave the wand"	"[Student] moves the wand slow then fast to watch it change, then slow again"

Category	Description	Example Notes		
Group 3	This topic includes notes for all students who began and ended the school year at 4 years old.	"[One student's] violence problems seem to have gotten worse after many attempts to get him into the classroom, [the teacher] says "… why don't you wash your hands and [use MindfulNest]""	"When using the wand,[a student] was calm for a little while, but as soon as something happened she went right back to hyper"	"[A student] was upset in the gym and they did flower breathing without the flower to help her calm down"
Group 4	This topic includes notes for all students who began the school year at 4 years old and ended it at 5 years old, or began and ended the year at 5.	"[Student] is able to move the wand slowly and realizes that when he goes too fast it turns red and the music stops, he then knows he needs to slow down"	"[Two students] were both using the squeeze and were very excited about finding the rocket ship"	"[Student] really understands how the wand works. He waves it really quickly and expects the music to stop. He got called away by the teacher and told me "I'll puts it back""

Table 4.4: Note category, descriptions, and examples for long term MindfulNest test findings.

The teachers in the classroom would often guide students (Figure 4.7) to use the tool when they noticed that a student was struggling with their emotions. If they were upset over something the teacher would list different things they could do to feel better, including going to MindfulNest. In these cases students would not always choose MindfulNest, sometimes opting for other options like simply getting a hug. When the students did go to the tool, they were able to use it to calm themselves down or to feel better. We also noted cases where the teacher did not suggest the students use MindfulNest. Often when children were throwing tantrums, the teacher would not allow for use, as the child might see the use of the tablet as a reward for their behavior. We also noted that teachers would talk about emotions in their morning circle time with the class as a whole. MindfulNest was either not used during this time or it was used, but teachers struggled to involve all students as it did not have support for a group setting.

Additionally, we observed specific students behaviors during the pilot tests. The first student group was three years old throughout the course of the pilots. We noted that this student was much less successful with the tool overall. At the beginning of the year, they would interact with MindfulNest purely as a toy. They did not follow the breathing on screen and instead would breathe on the flower as rapidly as possible to see it light up. They would use the squeezer simply to watch the balloon, not to release physical aggression. When using the wand, the student waved it randomly, and eventually stopped using it when the music stopped playing. They also were not able to successfully navigate the flow of the app. They could not pick their picture out as a way of indicating that it was their emotions. Instead they would click randomly in order to get to the activity they wanted to do. Within the classroom, we noticed that their language skills were not as developed as the other students, possibly explaining why they were not able to follow the prompts. As the students developed throughout the school year, their use of the app became a bit better. By the end of our test one student was able to properly select their picture from their classmates and navigate the rest of the app. They still struggled with the use of the manipulatives

Figure 4.7: A teacher guiding students through the use of the MindfulNest system in the long term pilots.

as calming activities, however they did make progress.

The second student group was age 3 at the beginning of the year, and turned 4 before the school year was over. We observed that their behavior with the app was much the same as group 1 towards the end of the year. They were able to use the app with mild success. They could use the flower and blow on it when prompted. They were engaged but not distracted by the flower lighting up. They were able to use the squeezer to make the balloon rise on-screen, occasionally focusing on the motions they were doing rather than the screen. From the beginning of the year towards the end of the year we did not note any successful use of the wand. Students in group 2 would pick up the wand and wave it, then put it away when the music stopped, rather than waving it slowly. However, we did see some success during the last couple of weeks of the pilot when the student was able to transition from waving the wand too quickly to waving it slowly and thoughtfully.

Figure 4.8: A student using MindfulNest during the long term pilot tests.

The third group was created from students of age 4. We observed that this student used the tool most out of the four case studies, as shown in Table 4.5. This student had the most emotional outbreaks in the classroom and needed the most support for dealing with these outbreaks. The teacher reported that they would often use MindfulNest to help the student and that MindfulNest

did help the student improve with their emotional development. MindfulNest gave them a way to talk about what they were feeling and what they needed to do to feel better. Students of this age group were more focused on the emotional aspect of the tool than the previous two students. They were able to successfully use all the manipulatives and understand their interactions.

Group	Number of Observed Weeks Without Use During Observation Period	Percent of Weeks With Tool Use During an Observation (18 total observed weeks)
1	2	89%
2	6	67%
3	1	94%
4	5	72%

Table 4.5: Frequency of use of MindfulNest by age group.

The final student group was created from the group of students who turned 5 throughout the year or were 5 for the whole school year. This student was the oldest and most able to navigate the app without intervention. From the beginning of the year, we noted the successful use of the tool and all three manipulatives. This student did not need the tool as much for emotional development, but would use it occasionally when they felt upset. The bulk of their use, we saw them exploring the technology. They would look at the app and tablet and try to find other things it was capable of doing. They also explored how the manipulatives worked, specifically with the wand. They would begin the wand activity, waving the wand slowly, then begin rapidly shaking it to see how it responded. They would also try to shake the wand faster to see if it reacted faster. Students in group 4 would also roll it around, or move it in unexpected ways (not shown as the example motion in the app) to see how it reacted.

4.5.4 Future Changes to MindfulNest

From these pilot tests, we plan to make a number of changes to the system as we continue developing it. First, we noticed the teachers would introduce emotions in a whole group setting, but MindfulNest does not have support for use in a group setting. We plan on developing a way to integrate MindfulNest into the group talks regarding emotion. We also plan to make changes to the hardware of the manipulatives to make them increasingly robust to use by Pre-K students. We also plan on creating a new manipulative that has better sensing capability for squeezing in all directions. We plan for this manipulative to become a better way to take out physical aggression, while transitioning the sea creature squeezer currently in use to a more fitting application, such as *cuddle a toy*.

4.6 Final System

The final flow of the application now begins with the students selecting their picture and being asking how they feel. Once selected they have access to every activity in the app, no longer

dependent on the emotion they feel. This was done to encourage students to actually choose the emotion they felt, not just the emotion linked to an activity they liked. The student then completes the activity and is asked to place their hand on their heart, with a visual to guide them. After they have done this they are asked how they feel after doing the activity. If they feel better, they are taken back to the student selection screen. If they say they are not feeling better, then they are given the option of doing more activities. This flow is shown in Figure 4.9. The final manipulatives consisted of the flower, the aquatic stuffed sea creature squeezer, and the wand. The updated system is shown in Figure 4.10.
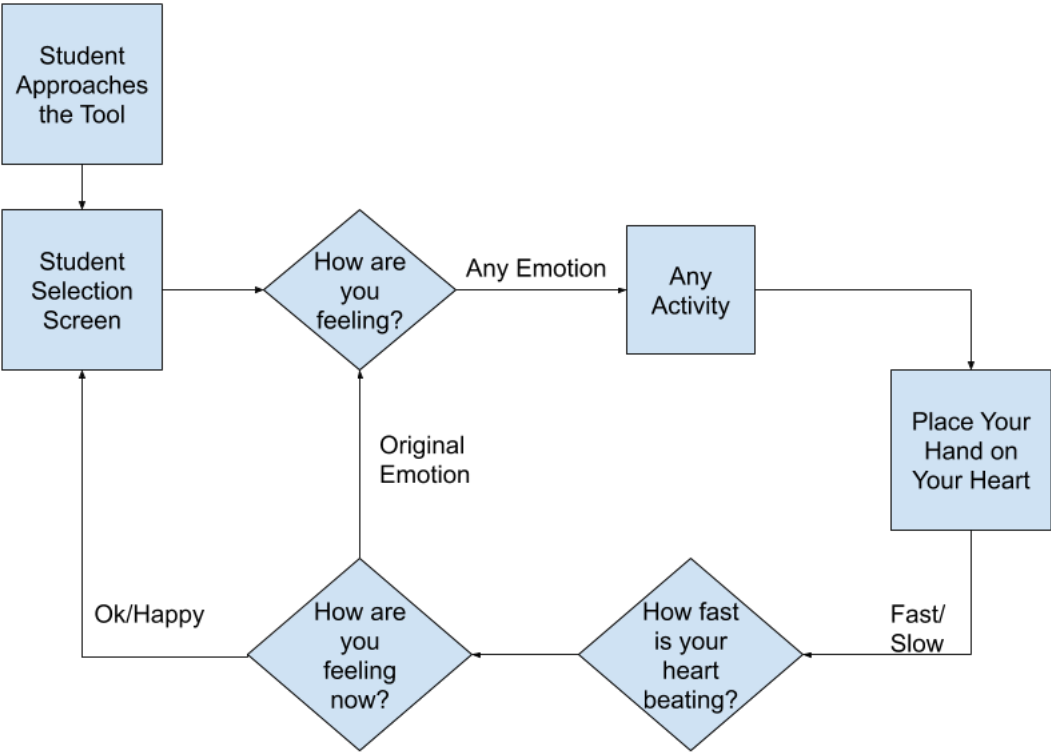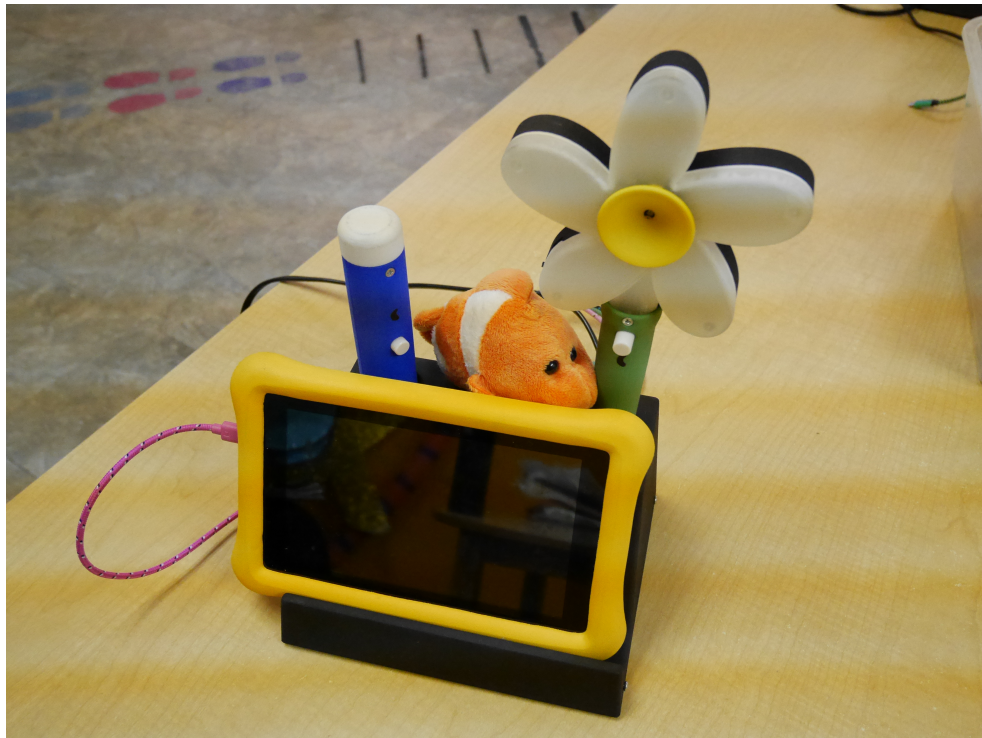

Figure 4.9: App flow of the final MindfulNest system.

Figure 4.10: Final MindfulNest system.

Chapter 5

Owlet

Owlet is a set of tools meant for use in Elementary classrooms (Kindergarten through 5th grade) designed to provide physical representations of the abstract ideas of different mathematical concepts. The suite is currently comprised of five apps and two physical robotic manipulatives. These are broken down into two systems, the Glow System and the Cube System. The Glow System is comprised of the GlowBoard, a robotic manipulative, and three apps: GlowGrid, GlowPix, and Fractions. The Cube System contains the CubeTower, a robotic manipulative, and two apps: Cube3 and Cube6.

5.1 Glow System

5.1.1 GlowBoard

The GlowBoard is a robotic manipulative with two dials and two buttons that control LEDs on the board as shown in Figure 5.1. The board has an array of 12x12 LEDs in order to support number charts for basic math operations including addition, subtraction, multiplication, and division.

5.1.2 GlowGrid

The GlowGrid app is aimed at supporting learning and practicing of arithmetic operations. It has five main sections: *Addition*, *Subtraction*, *Multiplication*, *Division*, and *Division with Remainders*. These sections are shown in Figure 5.2. Each section and its corresponding interaction with the GlowBorad are explained below.

1. **Addition** - Students model addition problems by adjusting the number of blue and red LEDs lit up on the GlowBoard. The left dial controls the number of blue LEDs and the right dial controls the number of red LEDs. Turning the dials clockwise results in increasing the number of LEDs lit, while turning counterclockwise reduces the number of LEDs lit.

2. **Subtraction** - Students model subtraction problems by adjusting the number of LEDs that are red or off. All LEDs begin lit a dull white color, then students turn the left dial clockwise to increase the number of red LEDs lit. They then turn the right dial clockwise to increase the number of LEDs that are off.

Figure 5.1: The GlowBoard manipulative.

3. **Multiplication** - Students model multiplication problems by adjusting the number of rows and columns in an array of lit LEDs. The left dial controls the number of rows illuminated and the right dial controls the columns. Both dials are turned clockwise to increase the number of LEDs lit. For example, the student would turn the right dial to 2 and the left to 4 to have 8 total LEDs lit in a 2x4 array.

4. **Division** - Students model division problems by modeling its associated multiplication problem. The left dial controls the divisor (one multiplicand) and the right dial controls the quotient (the other multiplicand). The divisor and quotient both increase when the dials are turned clockwise. The students control the dividend (quotient) indirectly with both dials.

5. **Division with Remainders** - Students model division with remainders much like they model division and multiplication, however here there is an additional column of LEDs that represent the remainder in the problem. Students use the left dial to control the divisor, or the number of rows, and the right dial to control the total number of LEDs.

 Each arithmetic section has five activities, listed below.

1. **Explore** - Students turn the dial on the Glowboard modeling an equation. This equation appears on the screen of the Kindle in the GlowGrid app with a virtual model of the Glow-Board.

2. **Make** - The app generates challenges for the students to make a target number in a given amount of ways. Like making 24 in 4 different ways.

3. **Solve** -The app generates arithmetic problems for the students to solve.

4. **Find** - The app asks the students to find the number missing in the problem.

(a) Addition: Explore

(b) Multiplication: Make

(c) Subtraction: Solve

(d) Division: Find

(e) Division with Remainders: Create
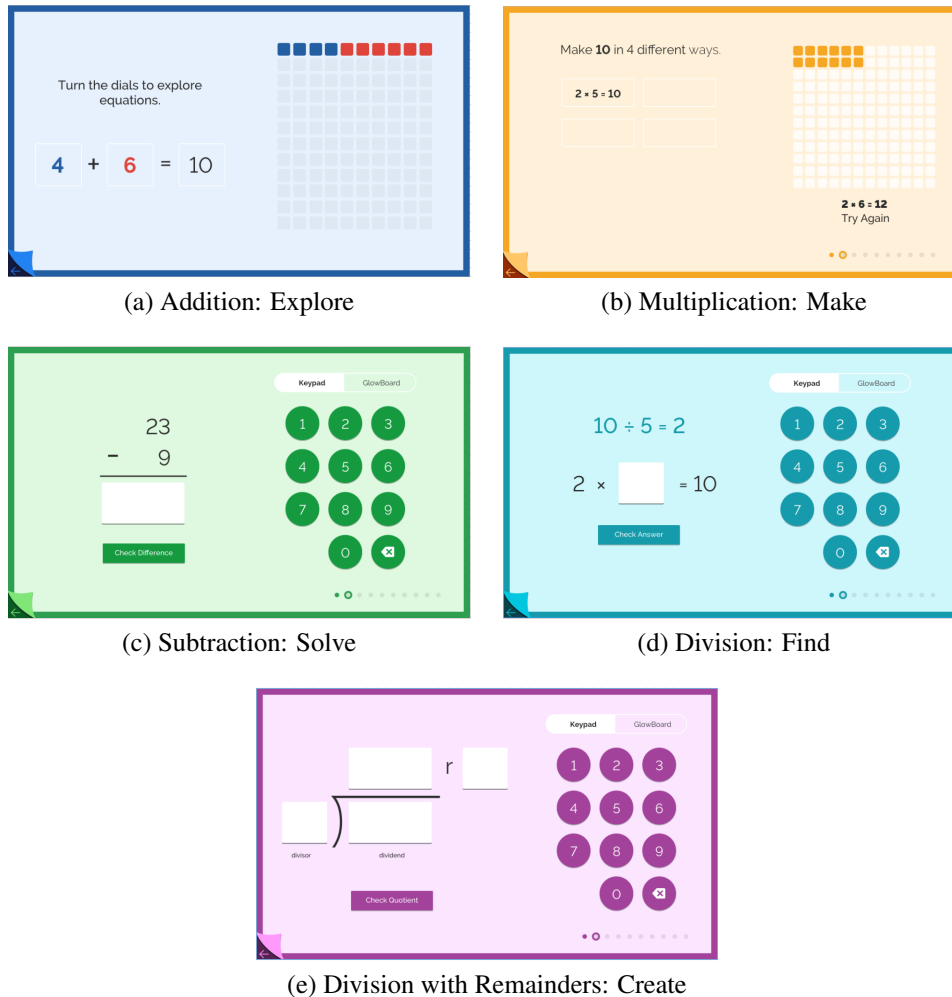
Figure 5.2: The different operations and activities of GlowGrid

5. **Create** - The app allows students to create and solve their own problems in the app.

Most sections of the GlowGrid app are supported with multiple difficulty levels, explained in the list below. The difficulty of the levels was determined by consult a number of different teachers for each grade level.

- Addition
  - Level 1 - All problems and Explore are limited to adding to 10.
  - Level 2 - All problems and Explore are limited to adding to 20.
  - Level 3 - All problems and Explore are limited to 120. Problems focus on adding by 10, generating at least one addin that is 10. Make is excluded for this level.
  - Level 4 - Numbers are limited to 1 to 120. Problems generated will not require regrouping. Make is excluded for this level.
  - Level 5 - Numbers are limited to 1 to 120 with no restrictions on the generated prob-

lems. Make is excluded for this level.

- Subtraction
    - Level 1 - All problems and Explore are limited to subtracting from up to 10.
    - Level 2 - All problems and Explore are limited to subtracting from up to 20.
    - Level 3 - Numbers are limited to 120 and problems will include a number that is a multiple of 10. Make is not included in this level.
    - Level 4 - Numbers are again restricted to be between 1 and 120 and problems generated by the app will not require regrouping. Make is not included for this level.
    - Level 5 - Numbers are restricted between 1 and 120, with generated problems being unrestricted. Make is not included in this level.

- **Multiplication** - Multiplication allows teachers to select only those numbers which they wish the students to see in the problems. For example, if a student has trouble with their 7's tables, the teacher would select only 7 in the levels menu.

The Explore and Make activities require students to use the GlowGrid as an input method in the GlowGrid app. The Solve, Find, and Create activities allow students to type in numbers and use the GlowBoard only when they need the support.

5.1.3 GlowPix

GlowPix aims to support arithmetic operations fluency through a block-based programming interaction that allows students to build pictures on the GlowBoard pixel by pixel. An example screen from GlowPix is shown in Figure 5.3. There are five levels for GlowPix explained below.

1. **Level 1** - Students start at a number and can create blocks that add/subtract from the previous number by one or ten. They are restricted to answers between 1 and 120 to stay on the GlowBoard aligned with the addition/subtraction number grid.

2. **Level 2** - Students start at a number and create blocks that add and subtract from the previous number. They are again restricted to solutions between 1 and 120.

3. **Level 3** - Students start at their given number and can add, subtract, and add three numbers to get a solution between 1 and 120.

4. **Level 4** - Students can add blocks that multiply, divide, add, and subtract by numbers of their choosing to get a solution restricted to be between 1 and 144. The number grid used is larger to allow for full use of the GlowBoard.

5. **Level 5** - Students on this level add an equals sign block and drag in any number of operations to one equation creating parenthesis and order of operations problems. Again they can use the full GlowBoard (1-144) for solutions.

5.1.4 Fractions

The fractions app aims to support students in learning and practicing fractions and fraction equivalence. There are three sections of the fractions app *Foundations*, *Intro*, *Equivalence*. Founda-
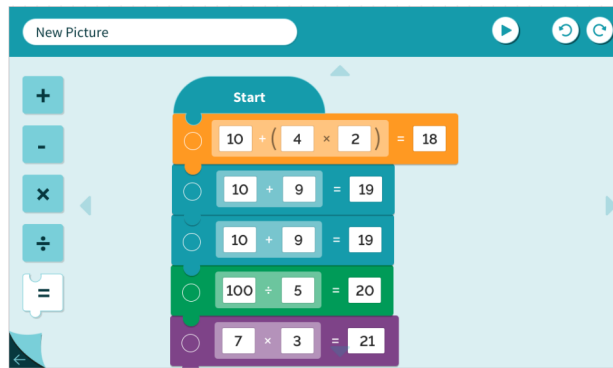
Figure 5.3: A sample screen from the GlowPix application.

tions and equivalence have Explore and Make activities. Intro has Explore, Make, Build, and Compare activities. Explore allows students to explore fractions in parts of shapes (Foundations), fractions in circles and bars (Intro), and the equivalence of two fractions (Equivalence). The different explore screens are shown in Figure 5.4. Make asks students to make a fraction or an equivalent fraction. Build asks students to build a number of fractions that are equivalent to a given fraction. Finally, Compare asks students to make two fractions and compare them. For each of the activities, the student uses the right and left dial on the GlowBoard to change the numerator and denominator, respectively.
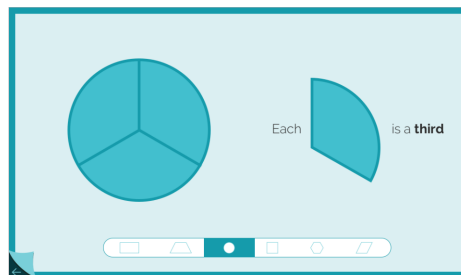
(a) Foundations: Explore
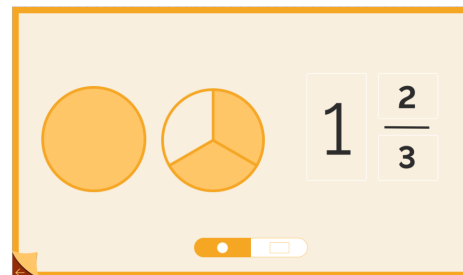
(b) Intro: Explore
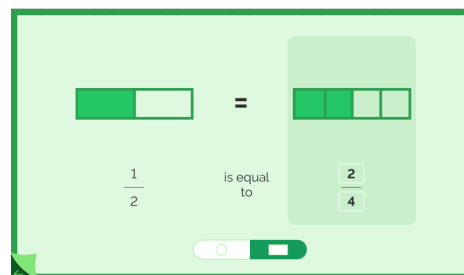
(c) Equivalence: Explore

Figure 5.4: Different screens from the Fractions app.
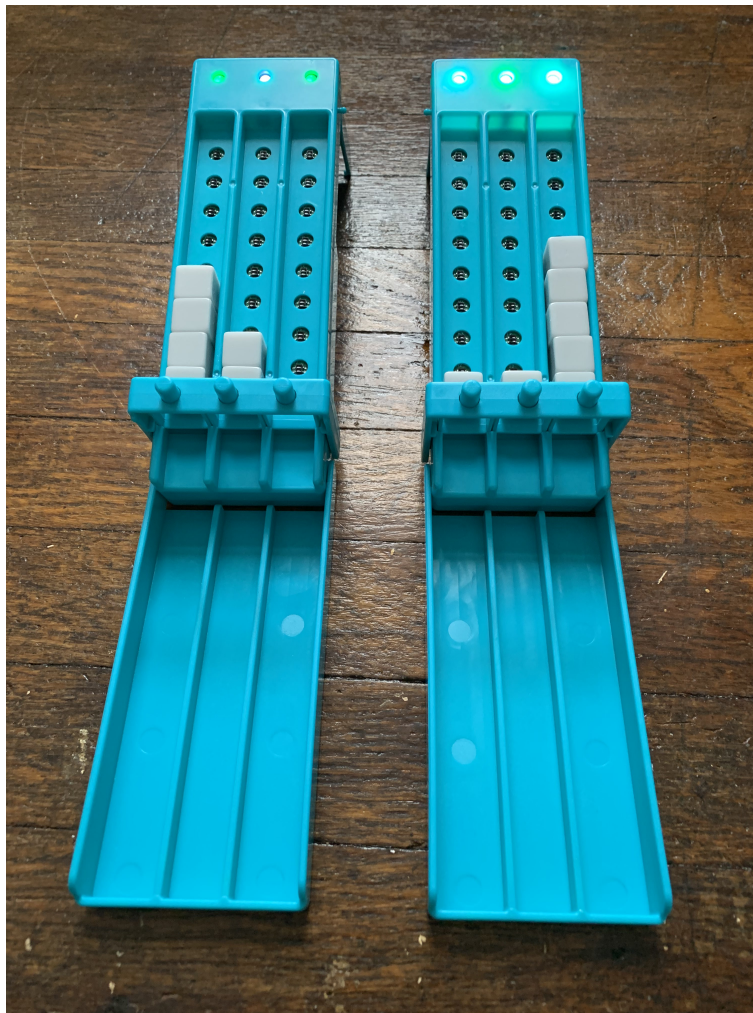
Figure 5.5: Two CubeTower manipulatives.

5.2 Cube System

5.2.1 CubeTower

The CubeTower manipulative is designed to ground place value concepts in a physical set of columns. Each column has room for 9 cubes, with an LED indicator on the top of the column to help students connect the apps and the manipulative. The columns have a release mechanism to allow students to clear each of the columns individually. The final CubeTower is shown in Figure 5.5.

5.2.2 Cube3

The Cube3 app has sections that support numbers with up to 3 place values. There are 5 sections: *Tens*, *Hundreds*, *Money*, *Hundredths*, and *Thousandths*. Money allows money valued up to $9.99. For each section, there are five activities described below and depicted in Figure 5.6.

1. **Explore** - Students add and remove cubes from the CubeTower to change the number on the screen.

2. **Make** - Students make a number in the CubeTower prompted by the app. The prompts in the app will vary in form from simply being the number to expanded or word forms.

3. **Build** - Students are given a number puzzle and must solve it by building a number in the CubeTower that fits the criteria. For example, build a number between 100 and 200 using 6 cubes.

4. **Compare** - Students create a number that satisfies the prompt in the app, then they are given a second number and must correctly compare the two. For example they are asked to build a number with a 7 in the ones place, and then they are asked to compare that number to 39.

5. **Round** - Students use the CubeTower as support to round a number to a specified place value given by the app.
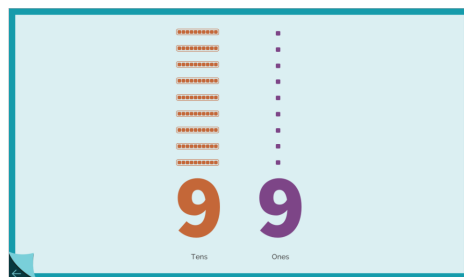
(a) Tens: Explore
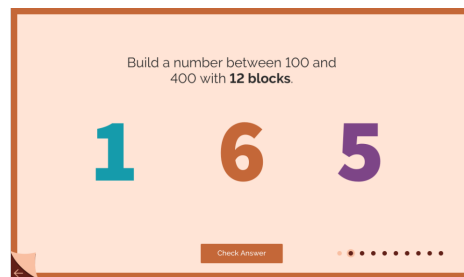
(b) Hundreds: Build
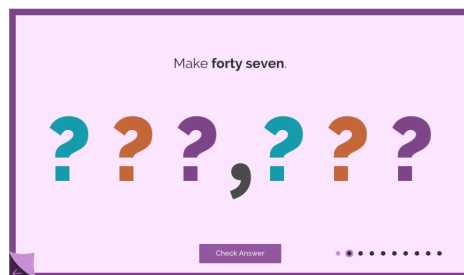
(c) Hundred Thousands: Make

(d) Money: Compare

(e) Decimals: Round

Figure 5.6: The different activities of the Cube3 and Cube6 apps.

5.2.3 Cube6

The Cube6 app supports numbers from four to six place values. The sections are: *Thousands*, *Ten Thousands*, *Hundred Thousands*, *Money*, *Hundredths*, and *Thousandths*. Money allows money valued up to $999.99. The activities for each section of Cube6 are the same as the activities in Cube3.

5.3   Development Process

Owlet started from another project called Arts and Bots [8] that integrated robotics into art curricula. From this the idea was generat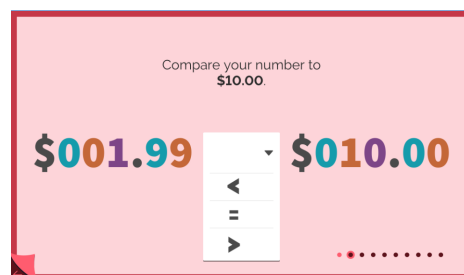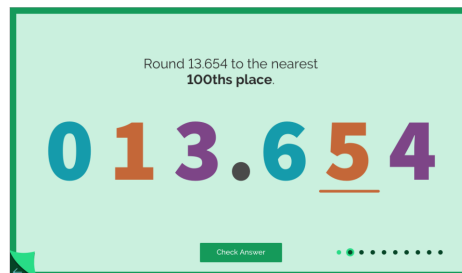ed to integrate robotic manipulatives into math curricula. Early-stage pilots [7] lead to the conclusion that these manipulatives had the potential to engage the students, but could also be too distracting from the concepts themselves. This helped inform our design goals for the final product. We aimed to design a tool that is

1. Intuitive for the visualization, exploration, and representation of abstract concepts.
2. Easily integrable into multiple math curricula.
3. Simultaneous engaging while not inherently distracting from math concepts.
4. Flexible enough to be used across grades K-5.
5. Supportive of math best practices, such as using multiple strategies to solve a problem.
6. Equitable for all schools by making a tool at an affordable price point.

We then ran four focus group sessions, developed two manipulatives and two apps for testing. Tested these systems, developed the Glow System further, and tested the final results.

5.4   Focus Groups

With our design goals in mind, we held a series of focus groups with 12 teacher participants with expertise across grades K-5. We recruited two 1st grade teachers, two 2nd grade teachers, two 3rd grade teachers, four 5th grade teachers, one instructional technology specialist, and one 3rd-5th emotional support teacher.

5.4.1   Session One: Brainstorming

The first of four focus group sessions focused on brainstorming goals and designs for potential tools. The session involved co-ideation between the researchers and the teachers involved in the process. We divided the teacher participants by their grade levels into three groups of four teachers each. Teachers were specifically asked what curricular areas have the highest and lowest student engagement, how classroom time with mathematics is typically spent, and what topics students struggle with the most. We also discussed with the teacher what kinds of technologies work best in their classrooms. Based on these conversations, we asked teachers to brainstorm possible ideas for technologies. We ended the session by converging back in the larger group and asking teachers to vote on the potential ideas that they had brainstormed.

Findings

During this session, teachers confirmed the research done in the area of Elementary math curricula. We also gained insight into the areas that were most and least supported by traditional manipulatives already. Teachers reported that areas like Measurement already included engaging and effective manipulatives, while areas like Fractions were lacking such manipulatives. This led us to focus our tool development in three curricular areas: arithmetic, place value, and fractions. Through our technology discussions with the teachers, we learned that in order to integrate into the classrooms well technologies had to have certain affordances. Most importantly, technologies should visualize the students' progress and should not require them to log-in to the device before use.

5.4.2 Session Two: Paper Prototypes

For the second session of the focus groups, we created paper prototypes based on the ideas generated in the first session [34]. These paper prototypes represented apps and potential digital manipulatives for further development. To test these prototypes, we created groups of two researchers and two teachers each. The teachers in each group acted as students in a classroom. One researcher played the role of a teacher in this classroom and prompted the teacher participants to complete tasks as part of a lesson using the paper prototypes. The other researcher in the group acted as the computer and changed the state of the paper prototype as the teachers interacted with it.
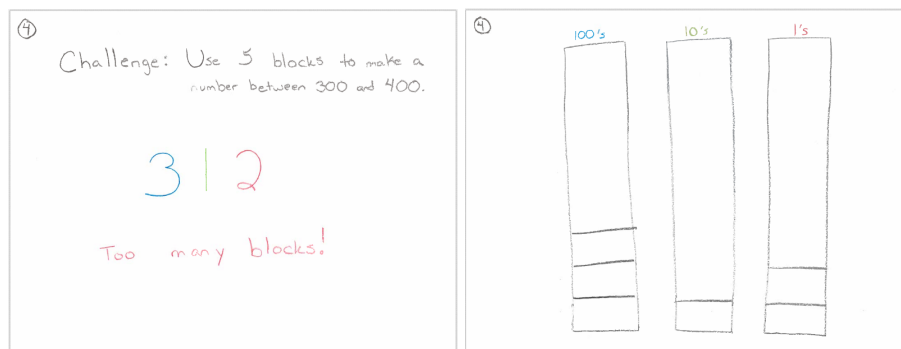
Figure 5.7: The paper prototype for place value concepts. On the left is the prototype of the screen; on the right is the prototype of the potential manipulative.

We tested ten total paper prototypes, two for each of: multiplication and division, fractions, addition and subtraction, place value, and drawing through arithmetic (which aimed to help number and operation fluency). The multiplication and division paper prototypes focused on learning and practice using an array of LEDs that would be controlled by the students through dials (Figure 5.9). Addition and subtraction focused on a similar manipulative with different functions. The fractions prototypes focused on interactions with a physical dial similar to the successful use of an early manipulative found in [7]. The place value prototypes focused on the idea of having number cubes and buckets to hold them for each pace value (Figure 5.7). Finally the drawing with arithmetic focused on different ways to draw using the equations. One idea focused on a

snapping block-based program to create a picture one pixel at a time (Figure 5.8). The other focused on creating rectangles of different sizes and width through geometry and multiplication. After teachers saw each prototype, they voted on their preference for the overall tool, the development priority of the tool, and the features included in the tool.
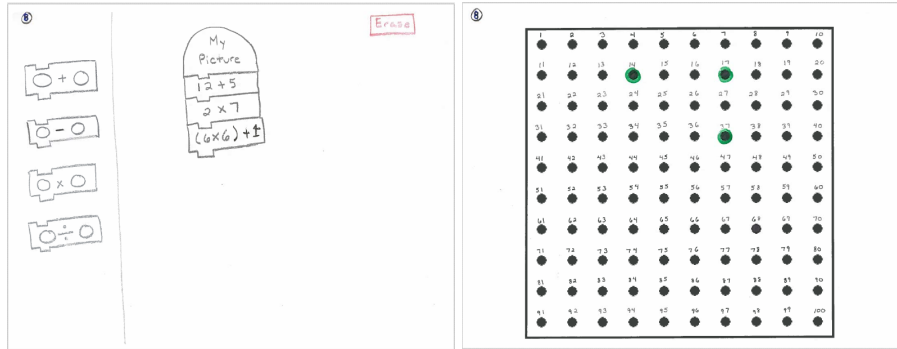
Figure 5.8: The drawing with arithmetic paper prototype screen (left) and manipulative(right)
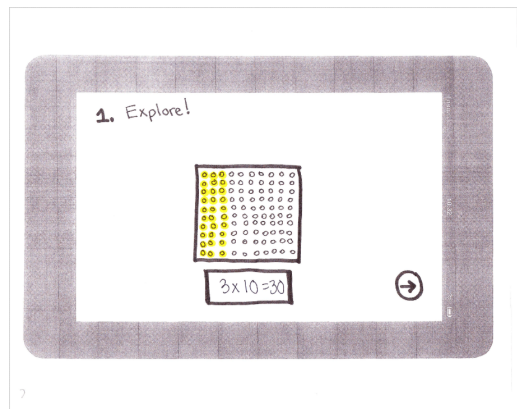
Figure 5.9: A paper prototype of the multiplication and division supporting tool.

Findings

The teachers showed the most interest in the place value prototypes. This led to the clear decision of continued initial development of a tool to support rounding, comparing, and arithmetic problems. However, there was not a clear consensus on the direction for the physical manipulative nor the features it should have. From here, we continued ideation and prototyping for the physical manipulative in later focus group sessions.

The next favorites of the teachers were the apps and the physical manipulative focusing on arithmetic. Among the six prototypes, the favorites included the block-based arithmetic drawing and all operations using the array of LEDs. Both of these app ideas were able to use the same manipulative device, aligning with our 6th design goal (Section 5.3). This device is called the GlowBoard and is a grid of LEDs that can be illuminated through Bluetooth or dial commands.

The arithmetic drawing app, which later became GlowPix, used a block-based programming method in which each block represented an arithmetic equation. By connecting blocks in the app, students could light up multiple LEDs on the GlowBoard to create a picture. The operations app, known as GlowGrid, focused on supporting different operations through use of the GlowBoard. We decided to prioritize the development of the GlowGrid app over the development of the GlowPix app as a similar app using block-based programming based on Snap! [3] has already been developed.

Finally, teachers expressed interest in having a tool to support students learning fractions. However, the teachers were divided on the options for fractions that we tested. This meant the fractions app would take much more design work and ideation to reach the same place as the other two ideas. For these reasons, we decided to postpone the development and save it for the second major development phase.

5.4.3   Session Three: Digital Prototypes

In the third session of the focus group process, we created six prototypes: two digital, two physical, and two paper. The two digital prototypes were in the form of a clickable Kindle screen. As teachers clicked on the screen the graphics would change depending on the location they clicked. Both digital prototypes depicted the GlowGrid app. One was focused on supporting the students in learning, the other was focused on supporting the teachers. The teachers explored each of the digital prototypes and gave their feedback on student and teacher interaction. Listing things they would want to see for students, and information they would want as a teacher about what the students had done during their sessions with the app.

The two physical prototypes explored different options for a physical manipulative to represent place value, shown in Figure 5.10. Both prototypes involved a tower structure with three columns for cubes to be placed, and a tray to catch the cubes at the bottom. One of the prototypes focused on just place value concepts with the three columns each only being able to store 9 cubes. The second prototype expanded on the place value concept to include support for arithmetic with place value as well. Each of the three columns had room for ten cubes before a removable divider was hit. Above this divider was room for 9 more cubes. This way students could build two numbers, remove the divider, and then create groups of tens and convert to a higher place value. Teachers had a chance to explore both physical prototypes and were then asked for their feedback on each one. Specifically they were asked about their preference of tool, the number of blocks that should be allowed in each column, and if/where there should be indications on the tool for supporting rounding.

The two paper prototypes focused on different app interactions for GlowPix. The prototypes explore different kinds of equation blocks, and fully generated problems versus missing number problems. Even though GlowPix was to be tested in the second round of pilots, we want to get initial feedback on the structure of the app from the teachers.

Findings

This focus group session helped us determine what should be developed for the first pilot process. The discussions for the student section of the GlowGrid app lead us to different scaffolding

Figure 5.10: Physical manipulative prototypes supporting place value concepts.

mechanisms that could be incorporated into the manipulative and the app. We decided that for the first set of pilots, it was more imperative to have the student section of all apps functioning before the teacher section of any app was developed. However, we still took the opportunity to get feedback from the teacher participants about the teacher section of the GlowGrid app. Teacher participants expressed interest in having the total number of questions students answered and the number and types of questions they answered incorrectly. Teachers also expressed interest in tracking this data over weeks or months as well. We incorporated suggestions made for both sections in designs and continued development for GlowGrid for the final focus group session and the first pilot.

The teacher participants gave mixed feedback for the place value manipulative. For example teachers were split on where the rounding indicator should be placed. Some enjoyed the support for addition with the larger columns, while others found it confusing. However, all teachers liked the three-column structure of the CubeTower and the physical act of place cubes within the CubeTower. We also collected feedback from the GlowPix testing, however, we did not continue the integration of this feedback until the second development phase described in section 5.7.

5.4.4 Session Four: Initial Usability Testing

In this session, we presented two prototypes to the teacher participants: an initial version of the GlowBoard and the GlowGrid app and a digital prototype of the CubeApp. The teachers were able to explore the interaction between the GlowGrid app and the GlowBoard during the focus

group. Teachers could turn a dial on the GlowBorad to change the rows or columns lit up on the GlowBoard, and the resulting multiplication equation would be shown on the GlowGrid App. This interaction was prototyped using the Flutter board [16]. We discussed the presented designs and designs for other operations and sections. Additionally, we discussed interaction with the dials and the LEDs for different operations with the teachers.

The digital prototype showed initial designs for the CubeApp. Teachers had access to the previous physical manipulative made for the third focus group session while they explored the CubeApp prototype. However, at this stage the interaction between the two was not available for teachers to explore. We asked the teachers about their design preferences for the CubeApp as well as additional areas or activities they would want included. We also asked them about potential interactions between the physical manipulative and the app.

Findings

During this final focus group session, teachers provided feedback about the usability of the tools and the interactions they had with them. For the Glow System prototype, teachers enjoyed the interaction between the GlowBoard and the GlowGrid app. However, they specifically noted that addition and subtraction should be on a grid with 10 numbers in each row while multiplication and division should be on a grid with 12 digits on each row. This would create visuals that better align with pre-existing number charts used in classrooms. They also wanted relevant vocabulary to be used in the app whenever possible to increase students exposure to the proper vocabulary. They generally liked that each section was color-coded and easily distinguishable.

Teacher participants also gave feedback on the CubeApp. They stated that they liked the clean design because it clearly did not resemble a game. They also stated that they liked the ease of use of the CubeTower manipulative, and settled on wanting a rounding indicator at the fifth cube spot of the CubeTower.

5.5 GlowGrid and CubeApp Pilot Testing

5.5.1 Systems

The tools tested during these pilots were initial prototypes of the GlowBoard, GlowGrid, CubeTower, and CubeApp. The state of each piece of hardware and software are described in the section below.

Glow System

The Glow System at this time consisted of the GlowBoard and GlowGrid. The teacher section of the GlowGrid had not been implemented at this time. However, each of the five operations had all activities listed in section 5.1.2. The GlowBoard had two limited-rotation potentiometers without detents that acted as dials. It also had 144 tri-color LEDs aligned in a 12x12 matrix. This size was selected due to the feedback given in the fourth session of the focus groups (section 5.4). The GlowBoard is capable of using only a subset of 10 columns of LEDs to better support operations like addition and subtraction. This initial prototype used the Flutter Board [16]. The
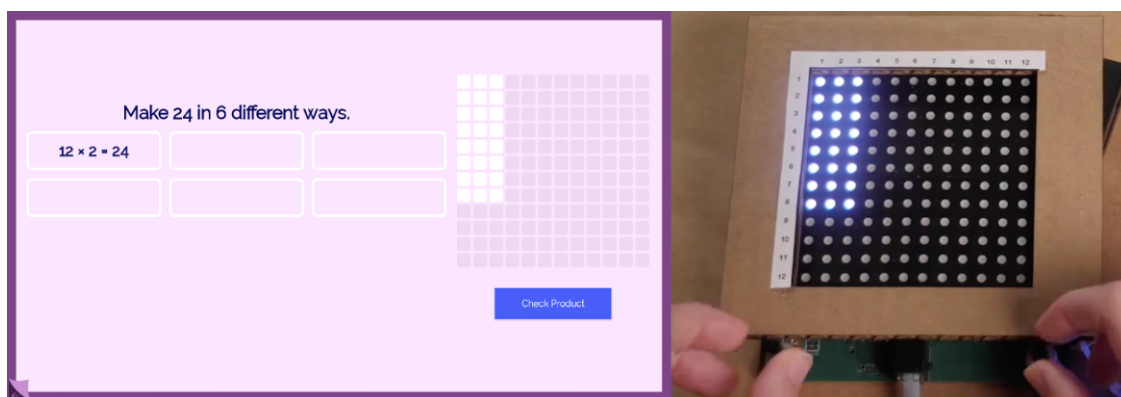
Figure 5.11: The initial version of the GlowBoard and a sample screen from the GlowGrid app.

dials would provide input to the Flutter Board which would have the operation information from the GlowGrid app, using all of this information the board would change the illumination of the LEDs on the GlowBoard. The initial prototype is shown in Figure 5.11. Due to inherent differences in function of operations, the dials would function differently for each operation. These differed slightly from the final operations, as did the levels. For each operation, dial use and levels available are listed below.

1. **Addition** - The left dial controls the number of blue LEDs, and the right dial controls the number of red LEDs. Addition has three possible levels to support students as their skills progress. Each dial controls 10 lights in level 1, 50 lights in level 2, and 100 lights in level 3.

2. **Subtraction** - Students select a number of bright red lights with the left dial and then turn the right dial to dim the lights to model subtracting them. Similar to addition, subtraction has three levels. Each dial controls 20 lights in level 1, 100 lights in level 2, and 120 lights in level 3.

3. **Multiplication** - The left dial controls the number of lit rows in the matrix from 1-12, and the right dial controls the number of lit columns from 1-12. The total number of illuminated LEDs represents the product.

4. **Division** - The left dial controls the divisor, and the right dial controls the quotient. The total number of illuminated LEDs represents the dividend.

5. **Division with Remainders** - The left dial is used to select a divisor from 1 to 12, and the right dial controls the total number of lights including the remainder.

Cube System

The CubeApp contained a selection of sections from across the final Cube3 and Cube6 app listed in sections 5.2.2 and 5.2.3. The cube app presented six place value modes: Tens, Hundreds, Thousands, Money, Decimals Less Than One, and Decimals Greater Than One. All activities were the same for each section as listed in section 5.2.2. However, the compare activity did not give the student any restrictions on the number they had to make.

The CubeTower, similar to the GlowBoard, was prototyped with the Flutter board, and is

Figure 5.12: The initial version of the CubeTower and a sample screen from the CubeApp.

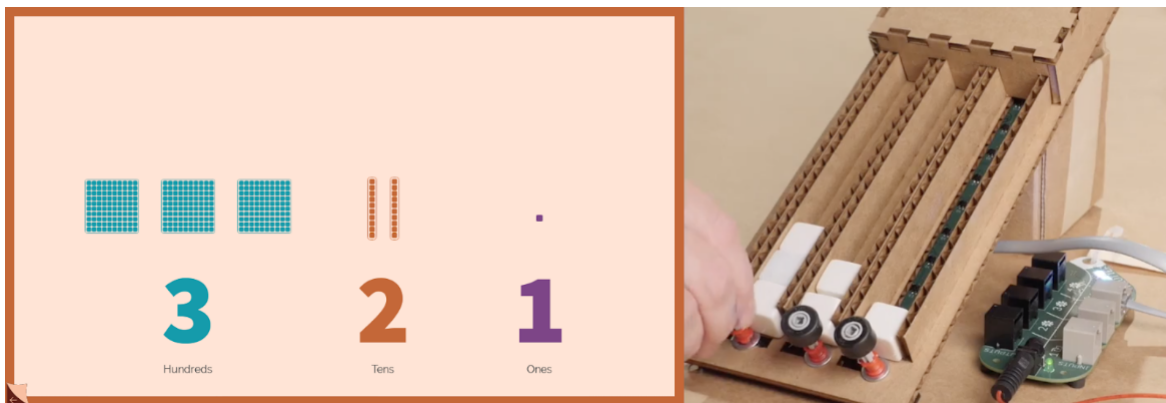shown in Figure 5.12. It was made from cardboard and had a rolling release mechanism for the cubes. The board has an array of IR emitter and receiver pairs that would detect the presence of a cube and communicate this information to the Flutter board which would then send this information to the CubeApp.

5.5.2 Research Methods

The initial round of pilot tests done included one test in each grade level from K through 5th grade. The students ranged from ages 5 to 11 and the pilots included 106 students (N=106). We used design-based research methods to test the tool appropriateness, usability, and applicability. The test schools included 2 urban schools, 1 suburban school, and 1 rural school. Before the test, teacher participants (N=6) were required to participate in eight hours of professional development. During these sessions, teachers learned how to use the manipulatives and accompanying apps, determined goals for use and classroom behavior, and planned daily lessons. Teachers participated in professional development with teachers of similar grades so they were able to discuss goals and lesson plans with each other. We provided teachers with system manuals and sample activities for certain lessons as a base point for integration into the classroom. Each test was planned to last five days in the classroom. The teachers chose which manipulative to use for three days and which to use for two days. At least two researchers attended each observation. During each session, researchers asked student participants about the tools and their opinions of them, noted students mathematical conceptions while they used the tool, observed how teacher participants integrated the tool into their lessons, and documented what troubleshooting was necessary for successful use. These notes were recorded as semi-structured field notes by the researchers. Researchers took notes regarding the following questions.

1. How do teachers apply Owlet tools to teach math?

2. How do students use Owlet to learn math?

Additionally, teachers were interviewed at the end of each test. They were asked questions about student engagement, project successes, and areas of opportunity and improvement.

Following each set of observations, the research team held debriefing meetings to review field notes, discuss themes in observations, and compile collective notes by grade. After all six

tests were complete, the team analyzed the collective notes which were classified by seven broad topics: 1) General Instruction, 2) Math Instruction, 3) Math Concepts, 4) UX/UI, 5) Software Limitations, 6) Hardware, and 7) Reactions. After coding by topic, the team coded each topic by theme, with two researchers per topic; the Cohen's Kappa for each topic can be found in Table 5.2. The results of this coding are discussed in the section below and described with examples in Table 5.1.

Topic	Description	Example Notes		
General Instruction	This topic pertains to instruction given in the classroom in general, not regarding math topics.	"Explore mode was quite flexible - first grade teacher also gave challenges like "how many different numbers can you make with 3 cubes?" 1st grade teacher only used explore. She didn't use make at all."	"Teacher had them explore all modes and activities - this didn't work well because the labels were then wrong for most of them."	"1st grade was not given any instruction about the order of using the knobs or the "make them bright, then turn them off" method for turning off the lights. They did not seem to do these things intuitively, so students may need more direct instruction or the dials may need to be more intuitive"
Math Instruction	Math instruction is any instruction given by the teacher regarding math concepts.	"Students used Addition: Find and tried to make their own strategies. Did pretty well."	"Teacher used the 10 sticks and 1s to introduce place value this morning. This was their first experience with place value."	"Teacher asks "how can [CubeTower] help us learn place value better?" Girl: "You can actually see it better if you can visualize it.""
Math Concepts	This topic pertains to all notes regarding math concepts, such as students discussing concepts.	"Teacher did several word problems with them and then let them challenge each other for a few minutes by making up word problems. Some tried to create subtraction word problems."	"Students were counting on their fingers and not using the board"	"Teacher realized that maybe their intuition for decimals wasn't as strong as she thought - they had only used paper and pencil before."
UX/UI	This topic describes the user experience and interface notes.	"Students did not grasp the concept of the dim versus the bright lights. They were confused as to why the right dial sometimes gave them bright light and sometimes gave them dim lights."	"Students learned how to connect pretty quickly. The colored lights on the board helped the kindergarten students connect."	"Teacher asked if the dials could be blue and red to help make the connection. Marked dials with colored scotch tape for the rest of the pilot."

Topic	Description	Example Notes		
Software Limitations	This topic pertains to the notes regarding software bugs and areas for improvement.	"With the same number, saw 20+ problems in a row be less than. When a smaller number came along the student answered less than because it was the trend and he got it wrong and just instantly put in greater than and went back to selecting less than"	"Board was disconnected and said zero and they just kept comparing to zero."	"One K girl gamed the system. When she got a hard problem, she would go out of the mode and back in and it would give an easier problem."
Hardware	This topic pertains to notes about the hardware itself.	"1st grade teacher wanted the GlowBoard to be slightly larger so it was easier to see the numbers on the overlay and count the dots without losing your place."	"Fair amount of disconnections - batteries? Are they turning it on and off?"	"The one with the battery pack is staying connected despite a lot of movement"
Reactions	This topic contains all notes about student and teacher reactions to the systems and tools.	""I love math now""	""I don't even want to do this any more""	"Girl: "The other day was not quite for kids our age, but [CubeTower] I could see us using. I like this.""

Table 5.1: Note topics, descriptions, and examples for GlowGrid and CubeApp pilot test findings.

Topic	Cohen's Kappa
General Instruction	0.80
Math Instruction	0.80
Math Concepts	0.76
UX/UI	0.74
Software limitations	1.00
Hardware	1.00
Reactions	0.74

Table 5.2: The Cohen's Kappa for each observation topic.

5.5.3 Findings

One major finding from the *Hardware* topic was that battery packs were much preferred to plugging the tools into wall outlets or extension cords. Another major finding was that the boards were disconnecting too frequently. We also found that the rolling knobs used to release cubes

were not easy for students to use and distracted from the main use of the tool. We also found minor fixes to apply to the GlowBoard Overlays.

One of the biggest themes in the *Software* topic was the students leaving and rejoining sections and the perceived trends in problem generation by students. Students were able to leave and rejoin activities and receive a new problem when they did not like the problem they were given. Students also noticed trends in the problem generation like consistently generating problems with the same answer. We also noted students had confusion regarding the display when the CubeTower was not connected to the tablet.

Figure 5.13: A teacher guiding a student through a multiplication problem using the GlowBoard and GlowGrid app.

For the *UX/UI* topic, we found both notes where the tools made sense and where they did not make sense. Most notes regarding the tools not making sense were about the subtraction section of the GlowGrid app. The students were confused about the interaction with the GlowBoard and how the dials represented the equations. The other notes in this topic were centered around the dials on the GlowBoard and modeling different kinds of equations with them. The notable experiences from the tools making sense were across all grades and for both tools.

For the *Math Concepts* topic, we found that over a quarter of the notes regarding math concepts were cases of purely successful use. Other notes included teacher correction of tool use and student self-correction when using the tool. Students when working in pairs were able to see the mistakes they had made instantly with the CubeTower and almost instantly with the GlowBoard and correct those mistakes. The teachers were also able to use the tools and manipulatives as a type of assessment in their classroom to gauge the level students were at. The other note category in this section was regarding times students did and did not use the tools. The CubeTower was required as the only input method to the CubeApp, however, the GlowBoard is more a supporting tool rather than an input device. The students were not using the GlowBoard if they already knew the answers to the problem. They also sometimes chose other strategies such as finger counting to support problem-solving rather than the GlowBoard.

For the *General Instruction* topic, we had notes for four categories. The first was classroom activities which described the kinds of activities that teachers were using in their classrooms to introduce the tool, within the tool, and to support the tool. Teachers used the explore activity

Figure 5.14: Students using the CubeTower and CubeApp.

to introduce the tool and build students understanding of how the tools worked. They continued using this activity to support types of problems not given in the apps such as word problems. We also found that the tool was well used in pairs and even allowed for students to correct each other. However, teachers had to take more than an ideal amount of valuable instruction time explaining how the dials on the GlowBoard worked.

For the *Math Instruction* topic, we found most prominently that students found multiple strategies and answers. Using the tools, the students were able to use different strategies to solve the problems, rather than being guided to use a single one. We also found teachers compared the standard manipulative used already in the classroom to help students gain insight into using the tools.

The *Reactions* topic highlighted student's liking the tool, being both engaged and disengaged with the tool, teachers liking the tool and their preferences and the grade level appropriateness of the tools.

5.5.4   Changes Made to Systems

The main changes made to the apps were regarding the ability to avoid more challenging problems and the problem generation of the apps. Both physical manipulatives were changed by removing the central Flutter board from the implementations. Each device would now have an encapsulated battery and Bluetooth capabilities within the tool itself. This will lead to easier classroom integration of the tools. The GlowBoard now uses new dials that allowed for continuous rotation to make it easier for students to control each dial. Both the GlowBoard and the CubeTower were prototyped in plastics for the first time. The cube release mechanism was also redone to be more intuitive and useful for students.

5.6 Summer Residency

In order to make the next steps in the development process, the team of researchers decided to conduct a residency of four elementary math teachers for two weeks during the development process. The four teachers were asked to spend ten days, in two five day periods, immersed in the tool development process. We first interviewed 13 teachers for the four available positions, and concluded on having one fourth grade teacher, one K teacher, one second grade teacher and one math specialist for grades from 1-5.

5.6.1 Week One

Week one was primarily focused on the further development of the Cube System and the Glow System and the development of the apps put off during the initial focus groups (section 5.4). The week began with brainstorming math teaching best practices. These best practices were used as a guideline for further development. Teachers reviewed the GlowGrid App and GlowBoard and gave feedback on both. They then helped brainstorm ways to fix some problems found in the initial pilots. The biggest discussion was centered around the representation of subtraction. This process was repeated for the Cube System. The teachers then went through four fractions prototypes. This resulted in the formation of two apps and paper prototypes for both. We then focused on creating a CubeOverflow app that taught addition and other arithmetic with carrying over. The conclusion of this discussion was that the physicality lent itself only to addition, and would not be worth the necessary doubling of the price of the CubeTower. The teachers also discussed GlowPix, Pattern, and Clocks apps.

5.6.2 Week Two

The second week began with a review of the best practices in order to frame the week with best practices. The teachers then reviewed initial hardware prototypes for the CubeTower and gave their feedback. They then focused on making paper prototypes of the apps discussed in the previous week. Notably the other apps developed all used the GlowBoard as an interactive manipulative. This furthered the idea that CubeTower was more rooted, but less flexible. The teachers also tested a working version of GlowPix and gave feedback. They then talked about and prototyped Fact Families, Pictograph, and Geometry and Angles apps.

5.6.3 Outcomes

The main takeaways from the weeks included getting rid of the CubeTower arithmetic sections. This concentrated the CubeTower on only place value and allowed the physical design to be more strongly rooted in the grounding of the concept of place value. There were also many app ideas generated for interaction with the GlowBoard. This emphasized the flexibility of the tool, but does not emphasize the physical affordance of the device. There was also much discussion through the week of different levels for students and how problems should be generated. Problem generation for the apps needed to be more intelligent than purely random generation.

5.7 Fractions and GlowPix Pilot Testing

5.7.1 Systems

The GlowPix app that was tested in the second round of short pilot tests included all levels in the final version of the app. The basic functionality of creating, deleting, and editing programming blocks was available in the app. Students were also able to change LED colors for each equation block and 'play' the picture at any point in their use of the app. The app did have some bugs that were known beforehand, such as pictures not saving and blocks occasionally not working as expected. These bugs were recorded, but not included in the final note review.

The fractions app included all planned sections for Foundations and Intro. The Equivalence fractions section had the Explore activity available. There were smaller elements that had yet to be implemented or were not fully implemented, such as stating the number of parts the fraction was currently broken into. Again, these were noted to ensure they were fixed, however, they were not included in the final note review.

5.7.2 Research Methods

For the second set of pilots, we tested in grades more targeted to the apps we were testing. We piloted the apps in one second grade (N=18), one third grade (N=25), and two fourth grade (N=17, N=19) classrooms. We again used design-based research methods to test the appropriateness, usability, and applicability of the apps. Before the test, teacher participants (N=4) were required to participate in 3 hours of professional development. During these sessions, teachers learned how to use the apps and accompanying manipulatives, determined goals for use and classroom behavior, and planned daily lessons. All teachers participated in professional development together and were able to share plans and goals during the sessions. We provided teachers with early versions of the teacher and student cards supporting the apps and manipulatives as a base point for integration into the classroom. Each test was planned to last two to three days in the classroom. The teachers chose which app to use for two days and which to use for a single day.

At least two researchers attended each observation. During each session, researchers asked student participants about the apps and GlowBoard and their opinions of them, noted students mathematical conceptions while they used the tool, observed how teacher participants integrated the GlowBoard and apps into their lessons, and documented what troubleshooting was necessary for successful use. These notes were recorded as semi-structured field notes by the researchers. Researchers took notes regarding the following questions.

1. How do teachers apply Owlet tools to teach math?

2. How do students use Owlet to learn math?

Additionally, teachers were interviewed at the end of each pilot. They were asked questions about student engagement, tool successes, and areas of opportunity and improvement.

Following each set of observations, the research team held debriefing meetings to review field notes, discuss themes in observations, and compile collective notes by grade. After all pilot tests were complete, we analyzed the collective notes which were classified into the same seven broad topics: 1) General Instruction, 2) Math Instruction, 3) Math Concepts, 4) UX/UI, 5) Software Limitations, 6) Hardware, and 7) Reactions. After coding by topic, we coded each topic by

theme. The results of this coding are discussed in the section below and examples are listed in Table 5.3.

Topic	Example Notes		
General Instruction	" Start with Foundations and Explore. Teacher demos both. Asks students to name the shapes as she does."	" Teacher rule - can only +/- 1 once [during GlowPix]"	" Made her own handouts (at the end). More structured than most pilots."
Math Instruction	" Teacher made sure to point out that the GlowBoard uses the 120 chart."	" On day 2 the teacher reminds students they can multiply and then divide. Teacher strategy - Take the number, multiply it by something, then use the inverse problem."	" When the teacher asks "Can you tell me what a mixed number is?" she is met with silence. She says "I'm sure you know but you are just forgetting right now." She walks them through changing the settings to level 2. They do Intro - Make. She says "Now you'll see a mixed number. Tell me what a mixed number is." A boy gives the answer."
Math Concepts	" Girl uses paper to draw boxes, trying to work out the math. Asks partner for help. "Help me get from 26 to 35." Partner: "10 and then you minus something.""	" Girl "What does 1 mean?" Partner girl: "1 means a whole.""	" Potential misconception - One pair had 1 11/22. "It's 1 1/2" "No, it's 1 11/22""
UX/UI	" When you tap on the number box, it should appear empty (currently looks like you can add to the number)"	" There were many cases when they brute force tried to solve intro: build questions. They would add one shaded part, check, then repeat until it was correct. In the case it was the last one, "Correct" would appear on screen, but they did not know what the actual fraction they made."	" One student got an answer wrong on purpose because she just wanted to see what the app did when you got it wrong."
Software Limitations	" Trouble connecting - there were a lot of devices moving around, tapping on the name didn't always make it connect. Update frequency was reduced for later pilots."	" Intro: Build is definitely more challenging, particularly if you get a larger denominators and have to go down (particularly 15, 15/18 is also a hard one)."	" BUG: SOME PICTURES ARE NOT SAVING!!!"
Hardware	"Bug: At least 3 devices - Hummingbird wouldn't disappear and I had to reboot."	"Bug: When you press play multiple times, the screen starts to flicker."	"Bug: As a group was working, all the lights on the GlowBoard turned white. The only thing that helped was turning everything off and back on."

Topic	Example Notes		
Reactions	" "I'm excited about math today!""	" "We're totally upping the pieces of pizza game""	" "I learned how to do it! I can do it by myself!""

Table 5.3: Note topics, descriptions, and examples for GlowPix and Fractions pilot test findings.

5.7.3 Findings

The *Hardware* code contained notes most related to occasional connection problems and display problems. The Software topic also noted some connection problems. The biggest software coding however, was about unintended behavior of the equation blocks in GlowPix. There were also noted areas for improvement in the user interface for the app, and potentially all the apps as the structure is similar. There were also bugs found in the level settings and problem generation of the Fractions app.
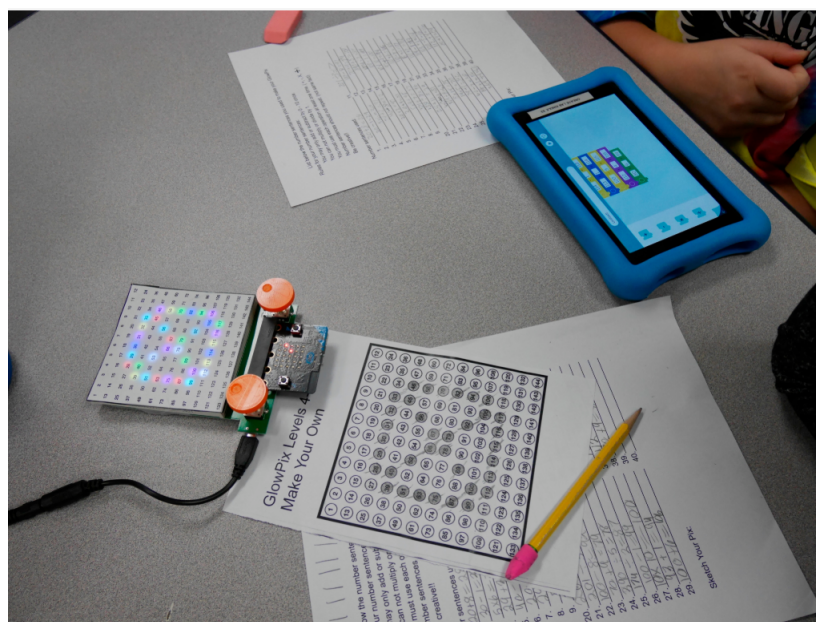

Figure 5.15: The GlowBoard showing a picture made in GlowPix with teacher made supporting worksheets.

The *UX/UI* topic had four prominent codings. One of which was the continued easy of connection for students. Students, even when they had not interacted with the app in a while, students were able to easily connect and start the app. We also noted that the dials were confusing to some students, they frequently forgot what the dials controlled which led to them adjusting more than necessary. There were also some notes about the Fractions app being hard to read as the text on the screen was too small. The last major category was regarding general confusion with the app and tools, such as prompts having only words and no icons.

The *Math Concepts* topic had prominent notes in the conversations that kids were having regarding math. During GlowPix, kids talked and strategized on how to use operations to get from the number they were on to the number they wanted to light up next. However, some pairs

would get stuck only using easy equations. Students also frequently needed support from other things, like paper, pencil, and number charts to complete the tasks. Specifically students found building equivalent fractions in Intro: Build to be challenging, and needed a middle step for problems that required them to simplify fractions first then multiple by the same numerator and denominator. We also noted students having misconceptions about fractions which might have been due to the lack of math language used in the app.

The *General Instruction* topic revealed interesting codes. The explore activity was not used as much by teachers for this set of apps as it was in the previous pilot tests (section 5.5). There were no additional problems given by teachers during the explore activity, they mainly used it as a way to show how the tool works. The teachers all spent time with individual pairs of students helping them with strategies to solve the problems given to them through the app. Another prominent code in the topic was that students would explore the app and tool without prompting from the teacher.

Figure 5.16: Students using the GlowBoard dials to control the fractions app.

The *Math Instruction* topic had two main codes. The first of which is the teacher supporting the manipulatives and apps with other things such as worksheets or charts from their curriculum. The other prominent note was that all teachers that used GlowPix limited the numbers and equations used in the pictures created by the students.

The *Reactions* topic had five prominent codes. The most common of which was that kids liked the tool. They were excited about using it during math class and wanted to start right away. The teachers also like the tool saying that it gave the students a physical way to interact with the math concepts. We also noted that kids found the problems challenging more often than they found things easy. There was also a code regarding the students not liking the activities and thinking they were boring. Usually this happened when switching to fractions after using GlowPix.

5.7.4 Changes Made to Systems

Based on the findings of these pilots, quite a few changes were made to the apps of the system. Most revolved around trying to integrate more number sense into the fractions app and balance what the app could show with what we wanted the app to do. We also decided to make changes to all the apps in both systems in order to make the interface more intuitive. We also looked further into the levels and the problems allowed and produced for both apps.

5.8 Final Glow System

5.8.1 GlowBoard

The GlowBoard is a robotic manipulative with two dials and two buttons that control LEDs on the board. The board has an array of 12x12 LEDs in order to support both addition and subtraction number charts and multiplication and division charts. The GlowBoard uses two dials with unrestricted range in order to allow students to input numbers. The buttons allow students to skip count by ten when pressed. The array of LEDs are tri-colored LEDs allowing for a selection of 8 different colors used to show a visual for connection of the board via Bluetooth to the app. The semi-unique BLE ID is hashed into a three-word name, and a three-color pattern to allow students of younger ages to connect easily. The GlowBoard interacts with many different apps in multiple manners, encouraging the learning of mathematics and basic robotic concepts.

5.8.2 GlowGrid

In the GlowGrid app the GlowBoard (shown in Figure 5.17) is designed to ground the abstract concepts of arithmetic through showing a concrete representation of the values being added/subtracted/etc. The GlowBoard takes the inputs from the dials and buttons, and determines which LEDs light up through an algorithm determined by the operation that the student is on. These inputs and changes in behavior based on the inputs introduce students to a very high-level concept of sensing, then determining actions based on this, and finally following through those actions.

5.8.3 GlowPix

In the GlowPix app, students are introduced to a sort of block programming that programs the LEDs on the GlowBoard (shown in Figure 5.18). The student is able to add blocks, delete blocks, and change the order of blocks. They are also able to change the problems they have and answer correctly to complete the block and light up the LED corresponding to the answer's numerical value. They also have the ability to change the color of the LEDs. This encourages the basic principles of programming, while also having students practice arithmetic fluency.

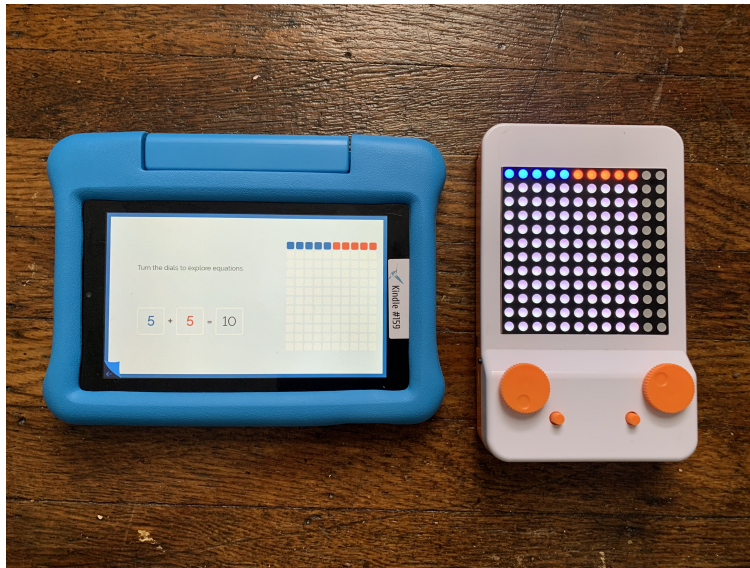Figure 5.17: The final version of the GlowGrid app in Addition: Explore with the GlowBoard modeling the addition equation.
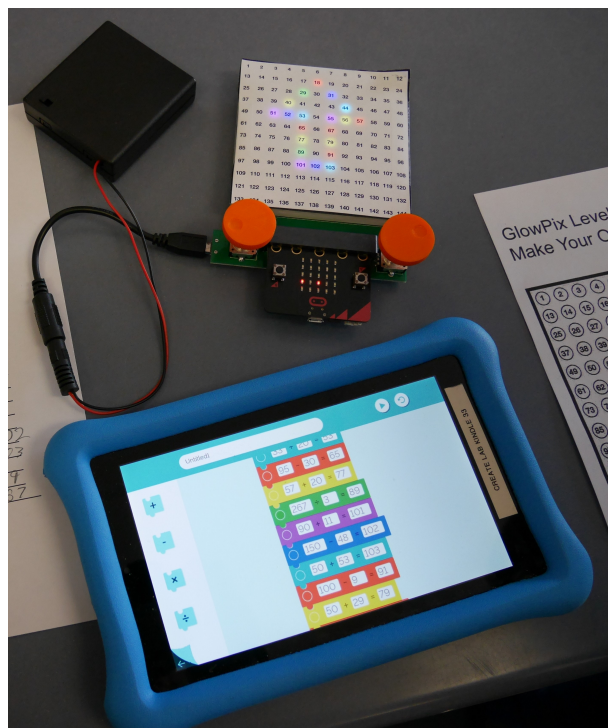

Figure 5.18: The GlowPix app with a semi-final version of the GlowBoard.

5.8.4 Fractions

The fractions app uses the dial as an input method to change the numerator and denominators of fractions on the screen. This is designed as a very basic interaction in order to focus on

Figure 5.19: The final fractions app with the GlowBoard.

relatively complex mathematical skills. An example problem in the Fractions app, as well as the GlowBoard are shown in Figure 5.19. The GlowBoard is used purely as input in this app, and so it displays a picture of a hummingbird on the GlowBoard while in use.

5.9 Final Cube System

The CubeTower manipulative is designed to ground place value concepts in a physical set of columns. Each column has room for 9 cubes, with an LED indicator on the top of the column to help students connect the apps and the manipulative. Each column is lit with the same color as is used by the text of the corresponding place value. The columns have a release mechanism to allow students to clear each of the columns individually. The cubes are detected by a set of IR transmitter/receiver pairs, one for each cube or 27 in total. The microprocessor determines how many cubes are in each column by detecting when IR is sensed passed a certain threshold. Once this threshold is reached, a flag is set marking that position as containing a cube. Once all flags are set for the column, the total number of cubes is determined by the position under the first position detected without a cube. This is used to decrease noisy readings and avoid conceptual dissonance between what is in the CubeTower and what is shown on the app. For example, if a cube becomes stuck in the top of the column in the 9's place with no cubes underneath it, the app would read zero rather than 9 (highest sensed cube) or 1 (total number of sensed cubes).

In the case of both Cube3 (Figure 5.20) and Cube6 (Figure 5.21), the CubeTower acts as the

Figure 5.20: The final CubeTower used with the Cube3 App.

sole input device for the app. The CubeTower sends readings to the app and they are displayed on screen. This simplifies the interaction between the two in order to focus on grounding the place value concepts in physical interaction. However, through exploration, more advanced students were able to deduce the underlying algorithms by blocking sensors with their fingers and seeing the outputs on the screen.
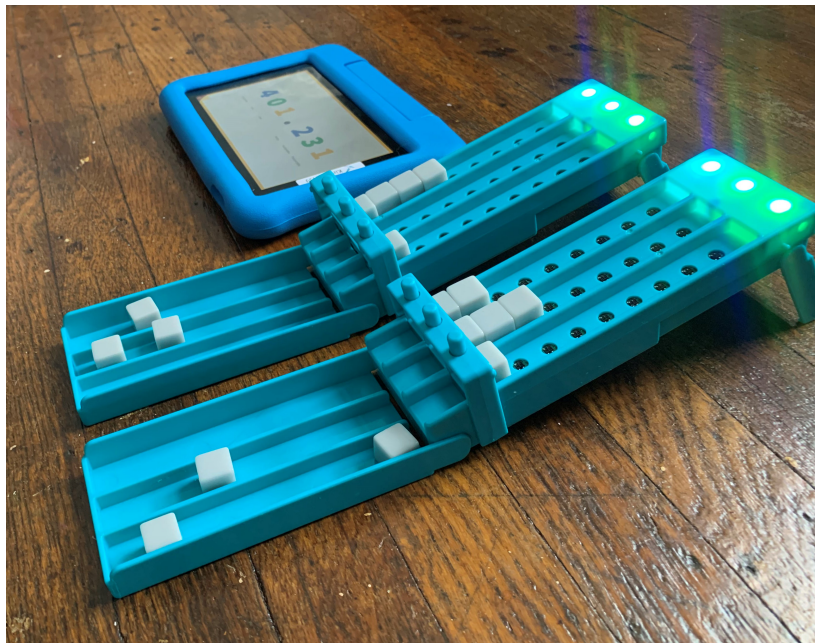
Figure 5.21: The final Cube6 App with two CubeTowers.

Chapter 6

Findings and Discussion

Overall pilot tests done on each of the systems, we observed that students were able to use the tools and follow along with the apps throughout their lessons. Not only were they able to use the systems, but students enjoyed using them and having them in their classrooms. Teachers as well enjoyed having the systems in their classrooms and were able to integrate their use into lessons easily.

6.1 MindfulNest

Through both the short term and long term testing with the MindfulNest system we found that it is possible to design a system that younger students are able to use. They were able to navigate the app well and interact with the robotic manipulatives as they were designed to be interacted with. Younger students struggled with the more detailed tasks like selecting their picture and answering questions thoughtfully. However, they were able to attempt all activities and follow the spoken prompts. Older students interacted more successfully, being able to reflect on their emotions and choose thoughtful answers to questions. They were also able to do all activities and follow the spoken prompts. Older students also began exploring the interaction between the manipulatives and the outputs they saw. Younger students would notice the LEDs on the flower changed depending on how they breathed on it, as well as the squeezer making the balloon rise. Older students noticed this as well as the wand changing colors depending on how quickly it was moved.

We also noted a number of successful classroom uses of the tool. For example the language surrounding the tool. If it was referred to by the teacher as a toy, students were more likely to play with it, rather than use it to calm down. We also noted that a check-in process each morning helped students become more familiar with the tool. Another note we found interesting was that students used the tool as the teacher modeled it, copying their interaction and use of the devices. When the teacher did not have a toy to cuddle, they gave themselves a hug and multiple students did this after that demonstration. The teachers, when interviewed, said they like the tool and wanted it in their classrooms again. They suggested changes to the system that were implemented or will be implemented that would make it better for the students and easier for them to use.

6.2 Owlet

Through testing of the Cube System and the Glow System, we found students were able to use them to support their mathematics practices. The direct connection between the CubeTower and the Cube Apps provided students an easy entrance into use and grounded the concepts of place value physically. However, less advanced students did not explore the algorithms and working behind the CubeTower. More advanced students were able to explore place value and also the algorithmic workings of the CubeTower. This encouraged them to think about the sensing aspect of the device, realizing what did and did not trigger the sensor to detect a block. And it also encouraged them to think about how the device determined the number of blocks in the Cube-Tower. If they blocked a position 2 or more higher than the actual number of blocks, the device would decide to ignore that reading.

The GlowBoard, on the other hand, had a less direct relationship between inputs and outputs. This resulted in a more abstract grounding than the CubeTower, but still provided the students with a physical way to manipulate the numbers they were using in their arithmetic operations. Though the students struggled initially with the use of the tool, they were eventually able to use it successfully to model arithmetic problems. By using the tool, they learn how the dials control the LEDs on each operation by reading the number of clicks from each dial, determining if the button was pressed during those clicks, and knowing what operation was currently in use and lighting up the corresponding number. The GlowPix app provided students more with the basic ideas of programming and less with a grounded representation. Conversely, the Fractions app provided a focus on the mathematical concepts and physically manipulating fractions, and less on robotic principles.

Teachers throughout the pilots were interviewed after each test and asked for their thoughts on both systems. Most teachers prefer CubeTower, but all said they like both systems. The teachers commented on different classroom uses they would want to be supported such as small groups and large demonstrations. They also commented on the setup and clean up time as well as the amount of physical space the devices and manipulatives took up. Based on this feedback, we modified the designs to be more compact and require less set-up before use.

6.3 Discussion

The CubeTower grounds place value concepts successfully in the physical world while providing students with instant feedback for their actions and almost instant feedback by allowing them to check their answers as they go along. The GlowBoard provides an outlet for students to understand the sense, plan, act model of robotics, while still providing some grounding in physical representations. These two systems differ in their abilities because they are made in different ways. The directness of the relationship between physical and digital aids in grounding, but detracts from the inherent learning of the more robotic principles of planning. The smaller the planning step, or more abstracted it is, the less the students explored that concept. With the Glow-Grid app, students had to learn the different ways to interact in order to use the GlowBoard. With the CubeTower, only students who were more comfortable with the interaction began exploring its inner workings.

A similar relationship was seen with the MindfulNest devices. Younger kids only understood the easier plan steps and older students were able to grasp the most intricate of these steps. However, this tool differed in that the interactions themselves were always grounded through a physical manipulative. The flower grounded breathing exercises, the wand grounded the slow movements, and the squeezer grounded tightening and releasing tension. The computation needed to get between the inputs and outputs of these devices ranged from fairly simple to more complex. The squeezer required only the activation of a switch to determine being squeezed. The flower required the capturing of breath, sensing of the sound it made on a microphone, and thresholding for final output. The wand required the sensing of angular velocity in three dimensions, manipulation to determine speed only in the arc in which it should be moving, and then classification of slow, fast, or no movement. However, even as the computation became more complex, it was always based on more simplistic concepts that students were eventually able to recognize.

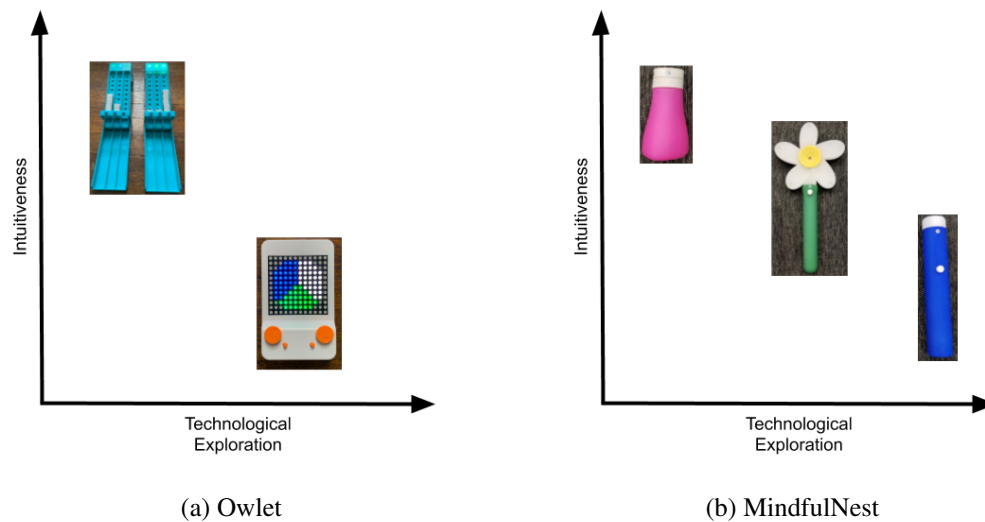| (a) Owlet | (b) MindfulNest |

Figure 6.1: Relationship between intuitiveness and technological exploration.

Through the observations of both Owlet and MindfulNest, we found an interesting inverse relationship between the intuitiveness of the device, and how much students explore the technology that went into creating the device (Figure 6.1). The CubeTower, which is very straight forward in the interaction with math concepts, was not as explored by students. Eventually, some more advanced students started exploring how the CubeTower worked to sense cubes, but most students did not. The GlowBorad, however, required students to explore the interaction between the dials and the board more as this interaction was not constant throughout the app. As for the MindfulNest manipulatives, when using the squeezer students did not explore further how the pressure was being sensed, they simply used it as an input device for the activity. While the wand was not explored by younger students, most of the older students would wave it in time to the music at first, but eventually would shake it rapidly to see what happened. They even stopped moving it or moved it in unexpected ways to see how it would react. The flower was explored a little bit by the students, however, the input/output relationship for the flower has fewer variables. This meant students were able to explore it more quickly and thus stopped exploring sooner.

Chapter 7

Conclusion

7.1 Conclusion

This thesis aimed to explore two major questions:

1. How can robotic manipulatives be designed such that they combine the affordances of both physical and virtual manipulatives?

2. How pedagogically usable and educationally effective are robotic manipulatives in Pre-K through 5th grade classrooms?

The first question focuses on the development and design of these tools. The goal was to design tools that combined affordances from physical and virtual manipulatives. The first of these design goals was grounding abstract concepts in the robotic manipulatives. This was reached with varying levels of success from the extremely direct connection that the CubeTower provides to the less direct connection of the GlowBoard. The second goal was to provide feedback instantly for students. This goal was met through either checking answers in the Cube and Glow Systems or through changing lights and screens in MindfulNest. The tools were also designed to be tangible for the students, which was achieved through all five devices, each having some sort of tangible manipulative for the students to use. Finally, the devices were ideally designed to offer a low effort entry point without requiring copious amounts of setup and cleanup time that distract from learning. This was again achieved in varying levels of success. MindfulNest was designed to be a station in a classroom that was always set up and available, requiring only that the teacher charge the devices at the end of the day. Initially the Cube and Glow systems required not only separate battery packs or plugs, but a separate connection to a Bluetooth enable board. This required more cleanup and setup time than ideal and was changed for the second iteration of the designs. Now they require no additional devices besides the Kindle and only require the teacher to charge them occasionally.

The second question related to the usability and efficacy of the devices in Pre-K through 5th grade classrooms. We found that teachers were able to use the devices, and enjoyed having them in their classrooms. They suggested small changes to the devices, but overall found them easy to use after participation in the provided professional development. The devices showed great promise for educational efficacy. MindfulNest was successfully used by Pre-K students from ages 3-5. Though younger students struggled they were still able to use part of the device, and

as they got older over the year they became more able to use the tool. Students learned what the inputs and output of the different manipulatives were and were able to explore them further. Owlet also showed potential for educational efficacy. Students used the devices successfully and were engaged in learning math with the devices. Teachers reported that students were more engaged with math than normal and much more excited for the lessons using Owlet. Students using CubeTower were able to directly manipulate physical objects to help them explore place value and eventually explore the device they were using to understand how it operated. Students using GlowBoard eventually learned all the different ways to operate it and had a physical outlet for interaction with numbers. Eventually through the use of Owlet and MindfulNest, students were able to explore the abstract concepts grounded in physical manipulatives and explore the concepts of technology that made these robotic manipulatives work.

7.2   Future Work

The work done in this thesis represents two projects still early in their development into full tools. The process began at the initial focus groups to create designs, through the testing of prototypes into the development of finalized systems. These systems will be tested further in order to determine further what the extent of their impact can be in the classroom.

MindfulNest will undergo a number of studies designed to determine the ideal age for students to learn the concepts of the tools and use the tools well, as well as a study determining if the manipulatives and the app are more effective in the classroom than traditional methods, or a version of MindfulNest with only the app and no manipulatives. From this study we also plan to study whether the app is a necessary part of the design at all or if the manipulatives alone can be just as if not more successful in the classroom.

Owlet also showed great potential for educational efficacy not only with mathematics but also with basic technology concepts. The studies conducted were short term and did not allow students to spend long amounts of time with the tools. The study planned to expose students to the tool long term and gauge the reactions and efficacy of the tool was delayed due to a global pandemic. However, we plan to conduct this study in the future to see how teachers use the tool over a school year and to see if it helps students' math or technology learning.

Beyond the planned tests, some questions are still left open. Given the times of global pandemic, educational technology is becoming more and more prevalent. These systems were designed to be cost-efficient and equitable. Given this they hold potential to be not only tools used in the classroom, but tools used at home in order to support learning. The systems do not require an internet connection in order to operate, however, they do require a tablet. With further work and development, these systems might have the potential to be easily used in homes. The systems might also be applied to other subjects besides math and social and emotional development. There is potential to support any subject with robotic manipulatives and integrate technology into the classroom.

There is also room for the tools to be improved and developed further. This thesis documented one approach to the larger question of supporting learning with robotics and more approaches could be explored. Another remaining question is how the underlying technology can be made more understandable and approachable without further distracting from the subject that the stu-

dent is learning when using the tools. Future work could be spent focusing on developing the tools further and applying the same development process to new manipulatives that span every subject.

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