Designing and Evaluating Smart Motors: Trainable Educational Robotics System for STEM Classrooms

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Abstract

Educational Robotics has gained popularity in K-12 education as an effective tool to teach STEM topics and skills like computational thinking, programming, collaboration, and creativity. With rapid technological progress, educational robots have found ways into classrooms worldwide. However, challenges like the ease of use, cost, and requiring specialized skills to operate and teach using these tools have hindered widespread adoption. In this dissertation, I present *Smart Motors*, a trainable educational robotics system, as a solution to these accessibility issues. By shifting from programming strategy to training, *Smart Motors* eliminates the need for computers and the internet to produce desired outcomes. Iterating through a series of improvements in design and components, we built a trainable robotics kit under $30. *Smart Motors* were used in several workshops and classrooms in different countries, and the results show that they can be integrated into STEM classrooms with students from second grade to high school. I present three proof of concept studies using three *Smart Motors* prototypes with different age groups in different settings from engineering design and arts to science investigation in order to show *Smart Motors* effectively fulfills the learning objectives. The usability tests on one of the prototypes with 7 to 15-year-old participants showed how they could discover the training features independently. It also showed that *Smart Motors* are highly likable and capable of producing diverse solutions quickly. Investigation of playful learning experience characteristics, while engaging in a play-based activity with *Smart Motors*, revealed that *Smart Motors* supports playful learning. Through collaboration with partners in the US, Brazil, and Nepal, we have created *Smart Motors* resources for teachers to introduce educational robotics in their STEM classrooms.

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Chapter 1

Introduction

1.1 Background and Motivation

Educational robotics is growing in popularity due to its impact on educational outcomes. Educational robots are effective tools to teach STEM (science, technology, engineering, mathematics) concepts [1, 2, 3], computational thinking [4, 5], robotics concepts [6] and computer programming [7]. Integrating robotics into the curriculum has been shown to effectively enhance soft skills like collaboration, interpersonal communication, creativity [8, 9], critical thinking, problem-solving [9] and inquiry [10]. Furthermore, educational robotics can be equally impactful in developing critical skills in younger children [11, 12, 13, 14]. Educational robotics have been shown to create interest in STEM disciplines for children who may not already be interested in STEM by integrating into arts and literacy programs [15, 16]. With robotics competitions, it has been shown that students who participate are more likely to choose a STEM career path in the future [17].

Several educational robotics systems, like the LEGO® NXT/EV3 [18, 19, 20, 21], VEX IQ kit [22, 23], iRobot Create® [24], KIBO [25, 26] have been widely used and studied in classrooms worldwide. However, despite educational robotics's popularity and benefits, some challenges have hindered access for many students and teachers. The major challenges with integrating robotics in curricula and classrooms have been identified as their high cost, lack of teachers' motivation and training, and lack of support to integrate robotics into the curriculum [27, 28, 29, 30]. There is a need for affordable robotic technologies that are geared towards diverse educational contexts [31]. A review of available educational robots listed and classified educational robots in use the classrooms and found that most educational robotics designers now consider low cost as a design feature [32], which shows the lack of low-cost options in the existing educational robotics catalog and highlights the resulting inaccessibility issue. Despite the challenges, some skilled teachers have invested their time and resources to build their own robotics systems to teach their students using open hardware and software platforms like Arduino and Raspberry Pis [33, 34, 35]. However, for most teachers who do not have the technological know-how or the resources to purchase expensive robotics sets for their students, the issue of accessibility remains one of the biggest challenges in educational robotics.

In 2020, The LEGO Foundation started an initiative called Tech & Play to create a network of partners to develop, practice, and research learning through play [36], focusing on coding, tinkering, and robotics. As the robotics specialist partner in the Tech & Play initiative, researchers from Tufts Center for Engineering Education and Outreach (CEEO) interacted with educational leaders and teachers from Brazil, Rwanda, Kenya, Nepal, and the US to discuss playful ways to bring

robotics and technology into the classrooms. One of the questions during our discussions was how we could introduce and teach robotics to students in remote locations, like the Amazon region, where schools may not have computers and internet access, and what that robotics system would look like. Tufts CEEO has years of experience teaching engineering and robotics, using different tools, including LEGO® robotics platforms. Still, this question took us back to the drawing board, as everything we had done so far used a computer to program the robot. In our brainstorming sessions, we made this our guiding question and came up with the idea of building a robotics system that can be trained with data instead of being programmed with a computer. This paradigm-shifting idea would have two implications: 1. By eliminating the need for computer programming, it would lower the barriers to entry for teachers and students who want to try robotics in their classrooms but don't have the technical know-how and resources to support it, and 2. By not requiring peripherals like computers and the internet connection it would significantly lower the setup and usage cost.

1.2 Research Questions

In this dissertation, I introduce *Smart Motors* as the trainable robotics system I have developed as an accessible, low-cost solution to educational robotics. This dissertation results from explorations with the *Smart Motors*. In this dissertation, I will define the *Smart Motors* system and how it evolved over the years through the engineering design process. We worked with designers, educators, and engineers to test the *Smart Motors* and provide constructive feedback. Over the years, we designed several STEM activities for different settings like museums, classrooms, and robotics camps and met with teachers who helped run those activities. The

workshops and tests were conducted to evaluate its usage in STEM classrooms. Here are the questions I am trying to answer through this dissertation work.

1. How can we design a $30 trainable robotics kit for a classroom with low resources?

   This guiding question led to the development of *Smart Motors*. The $30 price constraint was a goal we set for ourselves that would be comparable to the existing low-cost programmable microcontroller boards like Seeedstudio's Wio Terminal[1], Arduino UNO[2], Raspberry Pi[3] that are popular in schools. To explore this question, we used a full engineering design process of setting constraints, prototyping, testing, and redesigning multiple times. The development work involved testing different hardware configurations to meet the cost requirements, assembly techniques to ease the manufacturing process for interested teachers, and refining the user interfaces for ease of use. I used the product we built in classrooms without computers and studied how the users engage with it. I evaluated the usability of the final product, identified the pain points, and highlighted its features.

2. What are some ways *Smart Motors* can be integrated into the classroom to support STEM education? What results emerge through this integration?

   Educational Robotics has been proven to be an effective tool for teaching STEM in K -12 classrooms. In this dissertation, I seek to evaluate how *Smart Motors* can be integrated into the classroom to support STEM education as an educational robotics tool. Through workshops with students and participants of different age groups in different settings, I want to investigate

[1]https://www.seeedstudio.com/Wio-Terminal-p-4509.html
[2]https://store-usa.arduino.cc/products/arduino-uno-rev3
[3]https://www.adafruit.com/product/4295

the results that emerge from this integration.

3. What are some of the attributes of playful learning that *Smart Motors* facilitates in a play-based activity? What attributes emerge when users engage in a play-based activity with *Smart Motors*?

   Smart Motors was developed to encourage and facilitate playful learning in classrooms. Prior research has identified five characteristics of play in playful learning: Joyful, Actively Engaging, Iterative, Meaningful, and Socially Interactive [37]. I want to investigate the characteristics that can be supported through activities based on *Smart Motors* and where it might need improvements. While play can happen with any tool and may depend on other aspects of the activity, like activity design, activity time, and activity length, I want to investigate if there are some attributes that *Smart Motors* can facilitate through its affordance.

1.3 Dissertation Overview

The dissertation is divided into seven chapters. To answer a part of the first question, I describe the four major *Smart Motors* prototypes from Spring 2021 to Summer 2023. Then, to answer the second question, I present 3 proof of concept studies of workshops conducted using those prototypes. To evaluate the usability of *Smart Motors*, I ran a usability test with twenty-two 7-9-year-old novice users. Discussion of this test in the next chapter will answer the remaining parts of the first question. Finally, I will discuss the results of the analysis of characteristics of playful experience from the results of one of the workshops and the usability study to answer the third question. Below, I present a detailed description of what I will discuss in each chapter.

- Chapter 2: In Chapter 2, I will present the literature review on educational robotics and the current state of the art. I will discuss the engineering design process that I followed and its underpinnings in the literature. I will present an overview of the methods I used to discuss the results in the following chapters.

- Chapter 3: In Chapter 3, I will present a detailed description of the major *Smart Motors* prototypes. Since cost is one of our main constraints, I will provide the Bill of Materials required to build them. The prototypes were tested in workshops with the end users - students of different ages in different settings. I will discuss each prototype's design features and characteristics, which will help understand the studies described in Chapter 4. Without going into much detail, I will discuss the feedback and reflections for each prototype from the students and teachers and how it was used to design the next iteration.

- Chapter 4: As mentioned above, each major *Smart Motors* prototype underwent "real world" testing with students in classrooms and workshops. In this chapter, I will present three studies from 4 such workshops. The first study will discuss using *Smart Motors* in an engineering design workshop with found materials. The participants were novice users with no prior robotics experience. The second study will be about using *Smart Motors* in an arts and science class with second and third graders. The final study will discuss the results from two workshops with two different age groups, 4-6th graders and high schoolers. Through the studies, I will explore different ways *Smart Motors* can be integrated into a STEM classroom and investigate

the results that emerge from this integration.

- Chapter 5: In Chapter 5, I will outline the usability tests I conducted to assess the usability of the final *Smart Motors* prototype as of writing this dissertation. I will start by explaining the purpose of the usability test, the setup, and the method of data analysis I employed. I will then detail the activities and their respective outcomes. I will discuss through different metrics how the latest *Smart Motor* prototype satisfies the usability test.

- Chapter 6: In Chapter 6, I will present the findings of the characteristics of play in play-based activities using *Smart Motors*. I will use the Learning through Play Experience tool to evaluate the trends of states of play during the activities. I will use selected participants from workshops described in studies in Chapter 4 and the usability study in Chapter 5.

- Chapter 7: In Chapter 7, I will discuss the three research questions by reflecting on the discussions from Chapters 3, 4, 5 and 6. I will present some of our collaborative work with the partners in Brazil and Nepal in developing *Smart Motors* with locally available materials. I will also discuss future explorations with *Smart Motors* and conclude the thesis with a conclusion.

Chapter 2

Background and Literature Review

2.1 Educational Robotics

The foundational ideas of educational robotics are based on Piaget's constructivism and Papert's constructionism. One of the key assertions of constructivism is that the learner actively creates knowledge by reflecting on their experience and interactions with the environment [38]. Constructionism adds the role of conscious engagement to construct personally meaningful and public entities in constructing knowledge [39]. These ideas guide educational robotics in the classroom by emphasizing hands-on, experiential learning through building and programming robots. The beginnings of educational robotics in K-12 STEM classrooms can be traced back to the development of Logo programming language in the 1960s [40]. This pioneering work led to the development of LEGO® MINDSTORMS® line of robotics hardware and software through collaborative work between Seymour Papert's team at MIT Media Labs and LEGO [41]. With the development of ROBOLAB software for LEGO MINDSTORMS at Tufts, this platform reached millions of school children worldwide [42]. Due to its suitability to teach both adults and children [43], the

LEGO® robotics platforms have become the most popular commercial robotic kits available used in education [44, 45].

Figure 2.1 situates the field of educational robotics clearly as the intersection between Education, Robotics, and Human-Computer Interaction (HCI) [46]. In their paper, they defined educational robotics as *"a field of study that aims to improve the learning experience of people through the creation, implementation, improvement, and validation of pedagogical activities, tools (e.g., guidelines and templates), and technologies, where robots play an active role, and pedagogical methods inform each decision* [46]. In other words, educational robotics integrates robotics into the educational process, using them as tools and partners in teaching and learning to enhance the overall educational experience. I am mostly interested in developing the tool aspect of educational robotics and investigating alternative ways of eliciting behavior out of hardware.

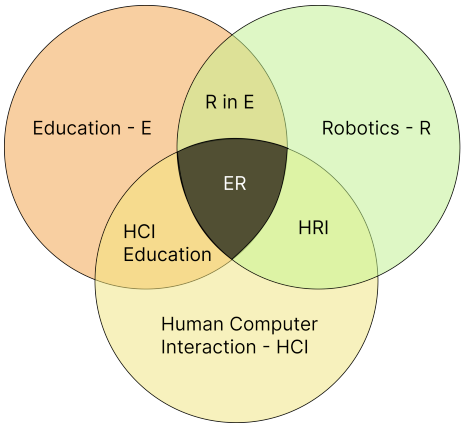


Figure 2.1: Figure showing the relationship between Education, Robotics and HCI and ER as an intersection of those fields. [46]

Several studies have been conducted in recent years to study educational robotics and their trends [47], application [48], and potential [49] in schools. Studies have identified various roles an educational robot can take in learning:

a tutor, peer, or a tool [50]. The early educational robotics, inspired by Logo programming and Turtle robots, mainly were focused on teaching programming but have now found use in teaching various topics like mathematics [51, 52, 53, 54], physics [55, 56], engineering [42, 57], computational thinking [58], storytelling [59], and soft skills like collaboration, critical thinking, and creativity [60].

2.2 Review of Existing Educational Robotics Platforms

There are many educational robotics platforms in the market. LEGO® NXT/EV3 [20, 21], VEX IQ kit [22, 23], iRobot Create [24], KIBO [25, 26] are some of the most popular educational robotics platforms that have been used and studied worldwide. Educational robots can be differentiated into DIY, Open Hardware, Brick-Based, Pre-Assembled, Specific purpose, Humanoid, and Tangible Programming [32]. Another way to differentiate is on the embodiment scale: Electronic, Mechanical, Humanoid [50]. They can also be differentiated based on a student's prior knowledge and programming skills required: No Code, Basic Code, and Advanced Code [61]. Finally, educational robots can be classified based on programming strategy: text-based programming, visual programming, and tangible programming [62].

I am mainly interested in the use of computers in programming robots, so I will focus on two types of categorization: based on the programming skills required and programming strategy. First, according to the paper classifying robots based on programming skills, The 'No Code' category includes kits programmed with a Tangible Programming Language (TaPL) that do not require computers [61]. Bee-Bot ($99.95)[1], Blue-bot ($129.95)[2], Pro-Bot ($159.95)[3] are some of the

[1]https://www.terrapinlogo.com/beebot-ss.html
[2]https://www.terrapinlogo.com/products/robots/bluebot-ss.html
[3]https://www.terrapinlogo.com/probot.html

examples of robots in this category. They are primarily coded with tangible buttons or keypads and are based on Turtle-Bot and Logo programming language. For example, Blue-Bot is programmed using a set of arrow and number keys mounted on the back to give instructions on the route that the bot follows step by step.



(a) Pro-Bot (b) Bee-Bot (c) Blue-Bot

Figure 2.2: Examples of robotic kits that do not require traditional programming knowledge or 'No Code' robots. [63]

Other examples of "No Code" robots are Cubetto ($225.00)[4], KIBO ($719.99)[5] and Ozobot ($175.00)[6]. They all differ in how they are programmed, but they are similar in that they do not require computers to program them. LEGO® Education SPIKE™ ($399)[7] also has a no code feature as a default program (HEART FUNCTION) that lets users program the robot by pressing buttons on the hub [64].

'Basic Code' robots are the ones that can be programmed using graphical programming languages or block-based programming languages like Scratch [8] [65], where code blocks are dragged and fit together like puzzle pieces or high-level text-based languages like Tickle [66]. LEGO® robotics platforms like now retired LEGO®NXT/EV3, LEGO® WeDo, LEGO® Education SPIKE™ Prime ($399),

[4]https://www.eduporium.com/primo-cubetto-playset.html
[5]https://kinderlabrobotics.com/kibo
[6]https://ozobot.com
[7]https://education.lego.com/en-us/products/lego-education-spike-prime-set/45678
[8]https://scratch.mit.edu

LEGO® Education SPIKE™ Essential ($320)[9] all fall under this category. Other robots like Thymio ($240)[10] also fall into this category.

And lastly, Arduino[11] and their boards like Uno REV3 ($27.60), MKR WiFi 1010 ($38.60), micro:bit ($17.95)[12], Raspberry Pis ($109)[13] are examples of the robots that require "Advanced Code". On a side note, Arduinos are cheaper than other platforms. However, the cost of advanced Arduino boards and shields can increase dramatically [67].

Another way of categorizing based on the programming strategy divides robots into text-based, visual, and tangible programming [62]. The text-based robots can be further divided into generic programming languages like C/C++ for Arduino, Python for LEGO® EV3 or Raspberry Pi or specific programming languages like ROBTOC[14] for VEX Robotics[15]. Similarly, block-based languages like Blockly[16], Scratch can be used to program robots like the robots from the LEGO® robotic platforms, Aseba for Thymio, which uses graphical elements like icons, symbols, to write the commands. Some robots use a combination of text-based and visual programming like Blockly, Tickle, and Scratch. Lastly, tangible programming refers to the method of programming robots through interaction with physical objects, similar to the "No Code" class of robots in the previous categorization. Examples of these robots are KIBO, Cubetto, etc.

Based on the two classifications, robotic systems that use "No Code" and Tangible programming strategy do not require computers to program them. They

[9] https://education.lego.com/en-us/products/lego-education-spike-essential-set/45345
[10] https://www.thymio.org
[11] https://www.arduino.cc
[12] https://microbit.org
[13] https://www.raspberrypi.com
[14] https://www.robotc.net
[15] https://www.vexrobotics.com
[16] https://developers.google.com/blockly

primarily use sequential programming with buttons or physical blocks. In the following section, I will further explore ways of programming a robot without computers that can be implemented in educational robotics.

2.3 Alternative Programming Strategies for Educational Robotics

As discussed above, there are different ways to program a robot, with text and graphics and simply by inputting a series of commands with buttons. In this section, I will review some methods that do not use a traditional programming method using computers or tablets, as one of our goals is to eliminate the need for computers to interact with robots.

Smart Trainable Robotic Arm [68] is an excellent example of programming a robot without a computer. This system has two modes of operation: 1) Learning mode and 2) Play mode. In learning mode, the onboard joystick moves the robotic arm, and the system stores the motor's position; in playing mode, the arm repeats the movement of the learning mode. This rudimentary system of repeating tasks can be a stepping stone to create a paradigm where the movements aren't necessarily temporal and can be altered by combining them with a sensor.

Interactive Evolutionary Robotics [69] is a framework with a reinforcement learning (RL) component. There are two modes: 1) Teaching mode and 2) Autonomous behavior mode. The robot's state space is defined in teaching mode, and rules are created based on instructional and environmental information. The teaching can happen in offline mode, where the instructor directs the action, or it can happen in a passive mode, where the robot demands direction for new environmental information, or in an active mode, where the robot performs explorations autonomously. This framework has been implemented on LEGO®

robotics platform where the robot evolved to perform behaviors like line following and wall following in a short amount of time [70]. A similar robotic platform was developed with a LEGO® SPIKE™ Prime and Augmented Reality (AR) viewer to show how the robot is making decisions [71]. The robot didn't require any programming by the user and only needed feedback (sometimes internally using the onboard IMU) on how it was performing, and in the end, it would learn to walk straight.

Deep imitation learning [72] is another method of teaching robots how to do specific tasks. In this learning method, the robots use a deep neural network to optimize the policy by imitating the expert. Deep imitation learning has many uses in autonomous vehicles [73, 74, 75], but I couldn't find much use in educational robotics.

There is another paradigm called Learning from Demonstration (LfD) where robots learn from dataset examples instead of experience as in RL [76]. In this method, a policy is derived from the examples during demonstrations, and the policy is executed in the real world based on the real-world state. The policy derivation could be done by mapping (k-Nearest Neighbors or Regression) or using the Reinforcement Learning type technique.

These are some methods of commanding the robot to do specific tasks and react to an environment without using a computer program. To summarize, we could build a platform where the robot follows specific instructions step by step, similar to the "No Code" or Tangible programming strategy. We could also build a system where the robot learns from datasets or examples by the users using algorithms like k-nearest Neighbors, K-means clustering, linear regression, or reinforcement learning. This would allow the users to train the robots with example datasets, and

the robot would create a policy to determine the action for the given environmental condition.

With the advancement and ubiquity of AI in society, the Association for the Advancement of Artificial Intelligence (AAAI) and the Computer Science Teachers Association (CSTA) have been working together to develop national guidelines for teaching K-12 students about artificial intelligence [77]. Different stakeholders have made several efforts to demystify AI in K-12, including the National Science Foundation's RETTL programs. Integrating the need to control a robot with a non-programming method and the importance of introducing AI in k-12 suitably positioned the envisioned trainable feature of *Smart Motors*. The implications of using a trainable robot in classrooms, especially for those who do not have access to a computer and connection to the internet, can be momentous in preventing the digital divide.

2.4 Methodology

This dissertation combines elements of the design process with research. At the end of each iteration of a design cycle, we gathered data through experiments in classrooms with the latest prototype available. The data helped us understand how *Smart Motors* can be used in classrooms, and it also informed the users' pain points, sometimes leading to the design overhaul.

We followed an engineering design process to develop the functions of *Smart Motors*. An engineering design process can be described as identifying a problem, understanding it better by researching and defining it, creatively generating possible solutions, evaluating them to ensure feasibility, and implementing them [78]. This process is iterative and may require several iterations to optimize to achieve the

desired outcome [79]. Each iteration starts by setting a set of design criteria, which is used to evaluate the alternative design solutions later [78]. Based on the problem statements, research is carried out to identify potential directions and solutions, and prototypes are built. Prototypes are the materialization of developers' ideas that can be evaluated by users or testers before production [80]. The development of physical products involves an industrial design process in addition to the engineering design process [81]. While engineering design focuses on function and innovation behind the product and process, industrial design focuses on the ergonomics and form of the product and process. Features like locally found materials to build, a simple fabrication method like a 3D printed box design, and simple and fewer steps to build and assemble would be some design constraints for replicability for teachers. Similarly, ease of use, discoverability of features, size, and weight that would be operable by a six or seven-year-old could be the design constraints for the student users.

Evaluation through user testing is an integral part of a design cycle. Some products and processes like drugs and medical equipment must undergo extensive user testing mandated by the regulatory organizations [82]. Even when not mandated, usability testing with actual users gives an insight into the users' mental models and helps developers identify issues that can be fixed in the next iteration. After the user interacts with the product, they can be asked a standardized questionnaire to calculate a metric defining the product's usability [83]. The other valid way of testing products is through expert review; stakeholders with extensive knowledge of similar products through study or experience can provide expert feedback [84]. After the user testing through classroom use, usability tests and expert review decisions are made on what features and design criteria need to be updated. This process is carried out in the next design cycle until all design criteria

are met.

To evaluate the use of *Smart Motors* in the classroom, I used an approach similar to a case study approach [85]. In education research, analyzing classroom data using video and audio recording is an excellent way of identifying patterns and acknowledging nuances that would otherwise be missed in field notes [86]. I used a proof-of-concept study to demonstrate the use of *Smart Motors* in STEM classrooms. Through the detailed analysis of the video data from the studies, I could present and discuss the results. This method allowed me to present examples of student works across different classrooms in various situations in great detail and tell clear and compelling stories so the readers can see how I am drawing my conclusions. To prevent the bias toward verification, which is one of the misunderstandings towards the case study approach [87], I use data from all the students from four workshops using three of our significant prototypes.

Finally, to evaluate the characteristics of the playful experience, I used the LEGO Foundation's Learning Through Play Experience Tool [37]. While the tool is designed for educators to improve the play experience of their students by carefully observing their data, it was an excellent fit for this study as well, as it allowed me to look at the nuances in the students' interactions, expressions, and overall activities in great detail.

Chapter 3

Development of Smart Motors

3.1 Introduction

In this chapter, I introduce the concept of *Smart Motors* and walk through its development by describing the features of significant prototypes. I describe the design constraints and how they inform the design decisions at each stage of the development. The description of each iteration is followed by feedback and reflections after testing with the target audience and reviews by the experts—fellow engineers, makerspace and museum educators, and stakeholders.

3.2 *Smart Motors*

A *Smart Motor* system comprises a motor, sensor, microcontroller, and user interaction peripherals. Based on the sensor reading, the algorithm determines the motor's state (position or speed). The microcontroller is pre-programmed with steps for storing and implementing the algorithm on the data. The main characteristic of a *Smart Motor* is that users do not need a computer or a programming device to program the system to achieve the desired output. It is also important to highlight

that the behavior of the motor is not predetermined and can be altered by the user through training.

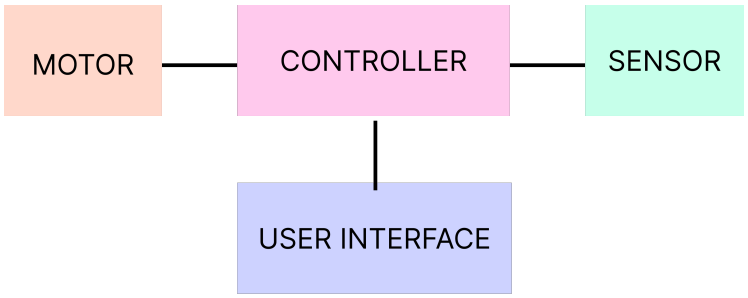


Figure 3.1: The schematic of a generic *Smart Motors* system components.

A *Smart Motor* system can be implemented using various microcontrollers, sensors, and motors. The choice of the microcontroller depends on cost, availability, and secondary features like WiFi or BLE connectivity, USB support, etc. Similarly, the motor can be a DC motor with or without encoders or a discrete or continuous servo motor. The system should ideally support a wide range of sensors, and users should be able to choose based on the requirements and nature of their project.

While the form factor, user experience, and usage depend on the type of microcontroller, motor, and sensor used, some standard features are distinct to *Smart Motors*. First, *Smart Motors* are trained to move to specific positions or run at particular speeds based on sensor readings. To achieve this, a *Smart Motor* system should have at least two modes to collect training data and implement the machine learning algorithm: *Training* and *Playing*.

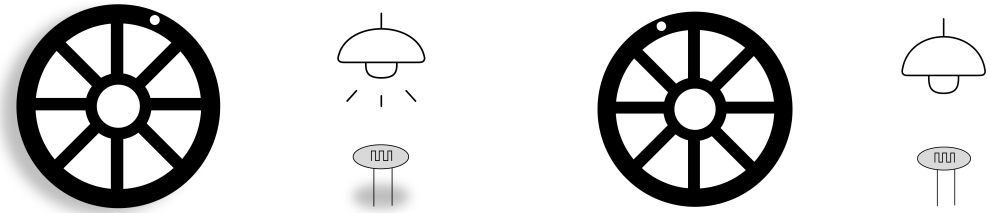
3.2.1 Two Modes: *Training* and *Playing*

In *Training* mode, the user records data by pairing the desired motor position (or speed) with corresponding sensor readings. The system uses the training data to determine how to respond to various sensor inputs.

In *Playing* mode, the *Smart Motor* uses a simple machine learning algorithm to determine the appropriate position (or speed) based on the current sensor reading and moves accordingly. This allows the motor to automatically adjust to real-time sensor inputs and perform the desired actions.

3.2.2 Machine learning algorithm

We use a simplified nearest-neighbor algorithm for all *Smart Motors* as a default machine learning algorithm. Nearest neighbor algorithms are easy to understand and implement and do not require extensive training datasets. They are supervised machine learning algorithms where users label the data. In the case of *Smart Motors*, each motor state is considered a unique label. The algorithm calculates the Euclidean distance between the calibration and current values in a 1D plane and selects the label or motor state with the smallest distance value. Since each training data is given a unique label, the value of k is set as 1 in all *Smart Motors* implementations.



(a) Representation of motor at position P1 and light sensor reading light value L1.

(b) Representation of motor at position P2 and light sensor reading light value L2.

Figure 3.2: Picture depicting different motor and sensor states to illustrate training data from *Smart Motors*.

Suppose the data pairings for the motor state (position or speed) and sensor

readings are given by (P_n, S_n) for n =1,2.... The sensor data or S_n is used to calculate the Euclidean distance, and the motor state or P_n becomes the label for the dataset. Suppose $S_{current}$ gives the current sensor reading. In that case, the label for the current sensor reading or $P_{current}$ is determined by comparing $S_{current}$ with all the sensor readings from the training dataset (S_n). If there exists a data point (S_x, P_x) such that $|S_{current} - S_x|$ is smaller than all $|S_{current} - S_n|$, then the label P_x is chosen and motor state $P_{current}$ will be set as P_x.

To illustrate with an example, consider a *Training* mode where a user saves two data points for states of motor and light sensors as shown in Figure 3.2. For Figure 3.2a, suppose the motor position is 60°, and the light sensor reading is 90%. Similarly, for Figure 3.2b, suppose the motor position is 105°, and the light sensor reading is 5%. The data pairs (60°, 90%) and (105°, 5%) are stored as training data where 90% and 5% are used to calculate the distance and 60° and 105° are used as their labels. Then, in the *Playing* mode, the algorithm uses the sensor reading $S_{current}$ to compare with both 90% and 5% to determine the value of $P_{current}$. If $S_{current}$ is 40%, then $P_{current}$ becomes 105°, as |40% - 5%| is less than |40% - 90%|. In this example, all sensor readings below 47.5% result in motor position 105° and above 47.5% in 60°. In the case of a light sensor reading of exactly 47.5%, the motor moves to 60° as the sensor readings will be compared in the order of data taken.

3.3 Development of *Smart Motors*

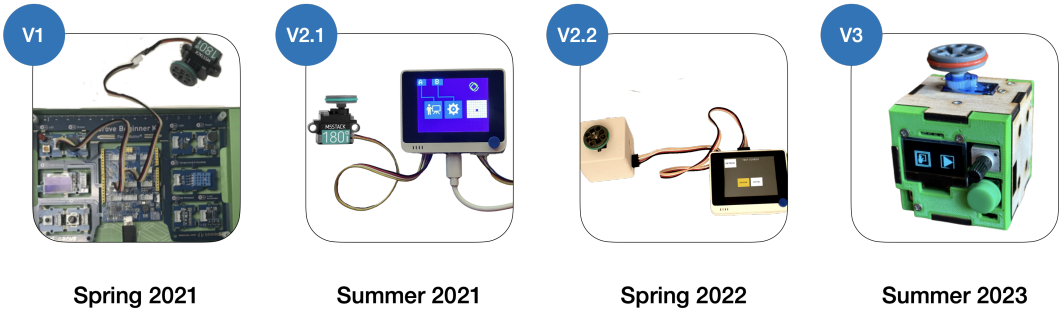


Figure 3.3: Timeline showing major prototypes of *Smart Motors*.

The development of *Smart Motors* can be divided into four milestones or versions as shown in Figure 3.3: V1, V2.1, V2.2, and V3. V1 is the proof of concept prototype developed in May 2021. V2.1 and V2.2 were developed around the same time, with the feedback from V1. Finally, the V3 is the latest prototype that combines all the features from V2.1 and V2.2 with improvements suggested by the users. Each version is described in detail in the sections below. In each section, I provide a short introduction and explain the features. I also reflect on the *Smart Motor*'s design results from workshops and expert feedback.

3.3.1 The First Prototype or V1

The first prototype, or V1, shown in Figure 3.5, was developed in May 2021 as a proof of concept of *Smart Motors*. It was based on Seeed Studio's Grove Beginner Kit[1]. We sent out several *Smart Motors* V1 to targets of convenience for evaluating the concept of a trainable robotics kit. They interacted with the *Smart Motor*, built projects, and shared videos of their interaction with other early testers. The group convened in an online hackathon on Zoom on May 14th, 2021, where they

[1]https://wiki.seeedstudio.com/Grove-Beginner-Kit-For-Arduino

built and shared their projects and provided feedback and suggestions for further development of *Smart Motors*.



(a) The Grove Beginner Kit used in V1 has an onboard microcontroller and a wide range of sensors to detect light, sound, humidity, and acceleration.



(b) The Servo motor from M5Stack used in V1 had connectors compatible with the Grove system.

Figure 3.4: The building blocks of *Smart Motor* V1.

Design Features

There were fewer design constraints for V1 since it was created to test the proof of concept of a trainable robotics kit. We wanted to prototype as fast as possible to start collecting feedback. But since we were in the middle of the pandemic, we couldn't meet in person to test and discuss. Therefore, we had to mail the prototype to early testers and ask them to take videos of their interaction. Shipping the kits to the testers meant avoiding kits with lithium-ion batteries to make shipping more accessible and safer. To simplify the assembly process, we looked for an existing kit at a relatively low cost, preferably with connectors or inbuilt sensors, so the users didn't have to spend much time getting the system up and running. We didn't want the testers to have to install applications on their computers, so we decided to install the codes before sending them away for testing to reduce their burden.

Here are the design constraints we were working with for the first prototype:

1. Off-the-shelf programmable microcontroller that allowed attaching sensors and motors without soldering
2. relatively low cost as we were planning to send these to as many testers as possible
3. Smaller form factor and lightweight to make shipping easier
4. Easy to power, preferably using a general USB cable

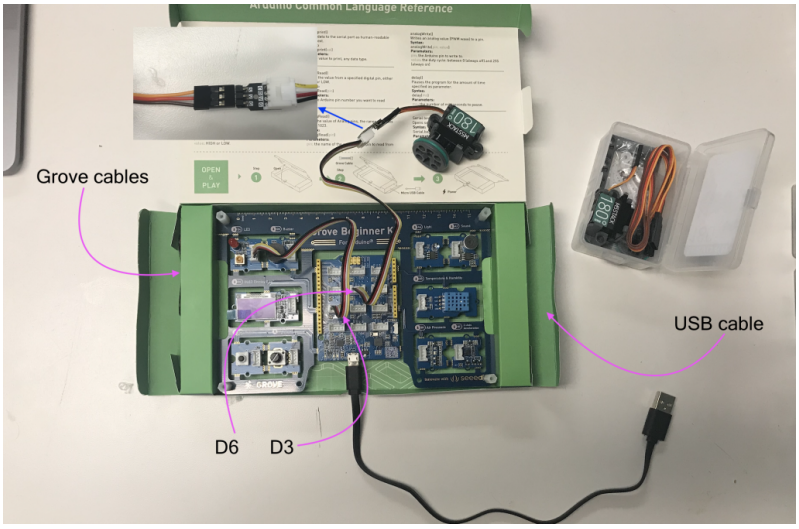


Figure 3.5: Assembly instructions for V1 *Smart Motor* with Grove Beginner Kit and M5Stack servo motor.

The V1 of the *Smart Motor* used the onboard button of the Grove Beginner Kit for data input and an onboard potentiometer to set the servo motor's position. The onboard light sensor was the input sensor, and the servo motor was connected to one of the onboard Grove ports for output. This version provided audible feedback using an onboard buzzer, but the user had no visual feedback. Once assembled, the system was powered using a micro USB cable plugged into a computer's USB port or a 5V wall adapter.

The system would start in *Training* mode and wait for a button press to prompt it to save data. In this mode, the user could move the motor by turning the potentiometer to their desired position. The system would save the motor position and light sensor value when the button was pressed. V1 was programmed to save 10 data points. After saving 10 data points, the system automatically switched to *Playing* mode, indicated by two short beeps.

Bill of Materials

The cost of materials used in V1 is given below in Table 3.1. The comparison of the price in 2021 and the current price as of 2024 is given in the third and fourth columns. The cost of goods saw a significant increase after the pandemic.

Table 3.1: Bill of Materials for V1 version of *Smart Motors*

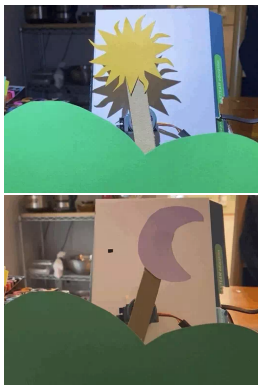
SN	Item	Cost in 2021	Cost in 2024
1	Grove Beginner Kit	$18.70	$22.99
2	M5Stack servo motor	$3.98	$6.48
	Total	$ 22.68	$29.47

Feedback and reflections

Early testers reported that eliminating the coding complexities allowed them to work on building projects with their young children. This freedom enabled them to focus on the sensors and projects without getting bogged down in technical details. They also mentioned that having additional sensors encouraged deeper learning and the ability to modify and improve their projects. Some testers expressed concerns about the lack of visual feedback on the system's status. Also, because the microcontroller lacked a file system, saving user data on the board was impossible.

This meant users had to retrain their motor every time the system was turned off and on.

Overall, the response was positive and encouraging. Participants in the hackathon easily learned to use the system and created and shared innovative projects. Figure 3.6 shows the screenshots of two projects created using *Smart Motors* V1.



(a) The light falling on the light sensor determines whether the Sun and or the Moon rise over the hills.



(b) A batter hits the ball at the right time when the ball covers the light sensor.

Figure 3.6: Examples of projects created using *Smart Motors* V1 and found materials.

Discussion

The first prototype of *Smart Motor*, V1, provided a strong foundation for us. It guided our thinking on the features to incorporate in the next version of *Smart Motors*. Although we received no negative feedback regarding the form factor of V1, we aimed to enhance the design to facilitate the integration of *Smart Motors* into design projects. Furthermore, challenges in shipping materials outside the United States prompted us to utilize locally sourced materials to develop *Smart Motors*, inspiring us to conceptualize *Smart Motors* as a versatile technology that could be implemented on various platforms. As a result, we began exploring the integration of *Smart Motors* into existing platforms such as Arduino Uno, LEGO® SPIKE™

Prime, and micro:bit[2].

3.3.2 Screen-based *Smart Motor* or V2.1

Development of the screen-based *Smart Motor* or V2.1 started in the summer of 2021 following the first prototype. We learned from the pilot study with teachers that the users would want the system to inform them of its various states. They described that it would be helpful for the system to communicate different sensor and motor values through a graphical representation. With that in mind, a microcontroller with a screen was chosen. The screen allowed us to experiment with different ways of displaying data, which was crucial in the further development of *Smart Motors*. Another addition to V2.1 was its ability to run the nearest neighbor and linear regression algorithms on the training data.

Like V1, V2.1 was made up of off-the-shelf products, so no fabrication was required. It consisted of three parts, as shown in Figure 3.7: a screen-based microcontroller, a servo motor, and a digital encoder.



Figure 3.7: Figure showing *Smart Motor* V2.1.

[2]http://smartmotors.ai

Design Features

V2.1 was programmed on Seeed Studio's Wio Terminal microcontroller[3] and consists of a servo motor and Grove rotary encoder. Wio Terminal's 2.4-inch 320 X 240 pixel color LCD screen was used for the user interface. The 3 configurable buttons and 5-way switch were used for user input. Among the two available Grove-compatible sensor ports, one was used to plug in the servo motor and another for the rotary encoder. V2.1 used the onboard light sensor and Inertial Measurement Unit (IMU) as sensor input, in addition to the rotary encoder.

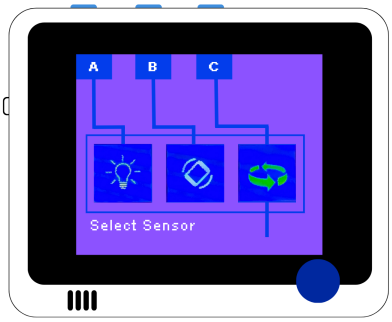
The tilt sensor was pre-selected as the default sensor in V2.1. The users had two options on the home screen shown in Figure 3.7; one, they could navigate to the sensor select page (Figure 3.8a) or the *Training* page (Figure 3.8b). Users could choose one of the three sensors available to train the motor on the sensor select page: a light, tilt, or rotary encoder sensor. The home screen also showed the selected sensor's icon in the top right corner, and an interactive graph below the icon showed the current reading of the sensor and motor position. The motor could be turned clockwise or anti-clockwise by pressing the 5-way switch left or right, respectively.

In the *Training* page (Figure 3.8b), users could pair the sensor values with motor positions by moving the motor to the desired position and pressing the 5-way switch while setting the sensor at a desired reading. A dot would appear in the grid showing the data was stored. Users could enter the *Playing* mode by pressing the C button with the play icon. In this mode, the motor responded according to the sensor values and the training data. In the *Playing* screen (Fig. 3.8c), users had the option to edit the data by pressing the C button. They also had the option to choose between the

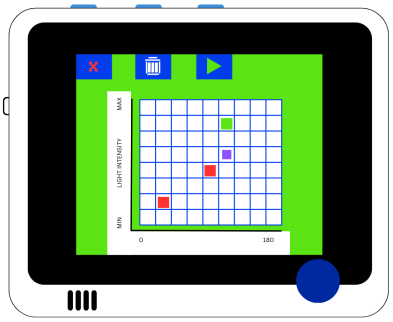
[3]https://www.seeedstudio.com/Wio-Terminal-p-4509.html

nearest neighbor algorithm and the linear regression algorithm on the training data (Figure 3.8d).

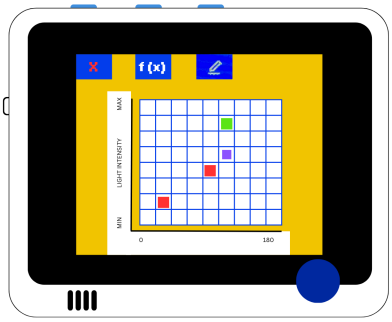
The data would not be saved on the system, so the users had to retrain the system with new data upon exiting the *Playing* mode page with the A button.



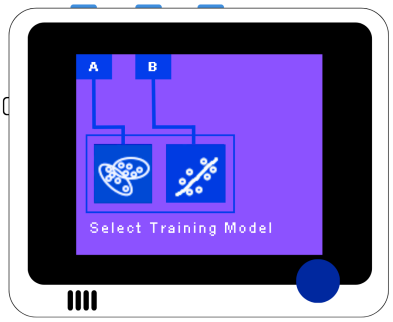
(a) The sensor select page shows options for selecting a light sensor, accelerometer, or digital encoder as the sensor.



(b) *Training* screen, where users could add data and delete data points. They could go to *Play* mode by pressing the C button with the play icon.



(c) *Playing* screen, where users could visualize the data, select the algorithm by pressing the B button, and edit the training data by pressing the C button.



(d) The training model selection screen allowed users to choose the nearest-neighbor algorithm by pressing the A button or the linear regression model by pressing the B button.

Figure 3.8: Figure showing different screens on the on *Smart Motors* V2.1.

Bill of Materials

The cost of *Smart Motor* V2.1 exceeded our cost constraint significantly. The price of Wio Terminal, the microcontroller and screen package, has since come down but

not within our cost constraint.

Table 3.2: Bill of Materials for V2.1 version of *Smart Motors*

SN	Item	Cost in 2021	Cost in 2024
1	Wio Terminal	$36.90	$29
2	M5Stack servo motor	$3.98	$6.48
3	Digital Encoder	$5.40	$5.40
	Total	$46.28	$40.88

Feedback and reflections

V2.1 was tested with middle school students in a 5-day robotics workshop in Nepal. It was also used to run a Novel Engineering [88] based activity with High School students on Zoom. There were issues with the user interaction. Users assumed the display was also a touch screen, so they would try to interact with the system by pressing the icons. The small 5-way switch was difficult to operate as a joystick. Users would accidentally press the button when they tried to move the motor.

The light sensor on the back of the Wio Terminal made it difficult for the users to look at the screen while taking data. It also meant they would have to use the Wio Terminal as part of the build when using the light sensor, making it difficult to interact with the *Smart Motor*. The position of the light sensor in the back also meant we couldn't use a battery pack to power the V2.1. Powering them using a USB C cable restricted the users' movement.

Discussion

The user tests with V2.1 were successful. The users learned to use the system with minimal instructions and created diverse solutions using *Smart Motors*. It showed

the importance of a visual medium informing the user about the state and data. It also helped us consider the input medium's size, placement, and affordance in future iterations. We learned about the limitations of having the sensors and user interface together. While V2.1 was compact and easier to use in the project than V1, it didn't support attaching building materials and integrating *Smart Motors* into the project. The off-the-shelf products let us build the prototype quickly to test the user interaction with the screen. They had many features, which inadvertently made them expensive, but they never got used. Thus, it prompted us to design our custom boards with parts optimized for seamless user interaction.

3.3.3 *Smart Motor Module* and *Training Module* or V2.2

Smart Motor version 2.2 (V2.2) was developed in the Spring of 2022 and consisted of a *Smart Motor Module* (SMM) and a *Training Module* (TM).

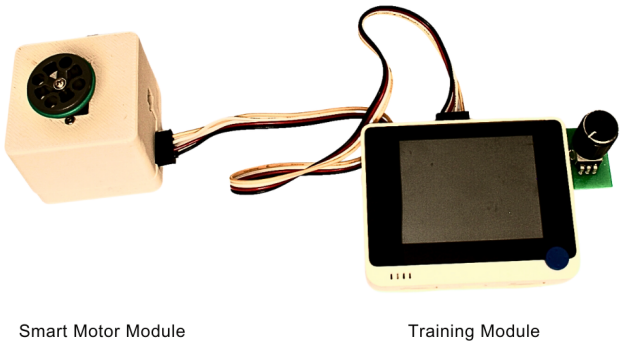


Figure 3.9: Picture showing *Smart Motor Module* and *Training Module* in Version 2.2 of *Smart Motors*

The detachable *Training Module* for the *Smart Motor* system was based on the following assumptions

1. Some users and applications may not require motor training. Therefore, a system that utilized existing training data to operate in *Playing* mode

out-of-the-box may be desirable in certain situations.

2. In a classroom setting, users only need to train the motor a few times. Hence, a detachable *Training Module* can be developed to be plugged in for motor retraining without affecting its functionality.

Separating the *Smart Motor* and *Training Module* could improve user experience. This could also improve and diversify the projects you could build with *Smart Motors*. We assumed the following could be the implications of having a detachable *Smart Motor Module* and *Training Module*.

1. Utilizing a screen and buttons for training on a separate module would minimize the clutter on the *Smart Motor Module* and maximize attachment surfaces.

2. As only a few *Training Modules* would be required in a classroom, removing components to train the motor from around 30 *Smart Motors* in a classroom would reduce the overall cost compared to having one *Smart Motor* per student.

3. A larger, more colorful screen would help users better understand the data.

4. Training Module could be used to perform additional functions like updating the *Smart Motor* and debugging.

Design Features

The *Smart Motor Module* included a servo motor and a custom printed circuit board (PCB) with a Grove-compatible sensor port, a communication port for interfacing with the TM, and an ESP8266 microcontroller. The 2-inch X 2-inch X 2-inch housing for the SMM was 3D printed. Due to some issues with the charging circuit,

we could not use an internal battery, so an external battery pack was used to power the *Smart Motor Module* using a micro USB cable for user testing.

Training Module included a Wio Terminal[4], a Wio Terminal Battery Chasis[5] and a custom PCB with a potentiometer and connector to communicate with the SMM. Wio Terminal is a SAM51-based microcontroller with a 2.4-inch LCD screen, a joystick, and 3 customizable buttons. The *Smart Motor Module* was programmed in micropython and the *Training Module* in C programming language.

Three polarized and keyed connectors were used on the *Smart Motor Module* to connect to the battery pack, sensor, and *Training Module* for easy connection and to help minimize connection errors. Figure 3.10 shows the connector types used on SMM.



(a) Micro-USB port used for power.



(b) Grove connector used for sensor.



(c) Rectangular connector with a latch for SMM-TM communication.

Figure 3.10: Different types of connectors used on *Smart Motor* V2.2 to mate quickly and error-free.

The *Smart Motor Module* could store the training data in its memory. So, when it was not tethered to the Training Module, it continuously operated in *Playing* mode and used the pre-existing training data to make decisions.

When turned on, the *Training Module* waited for the connection to the *Smart Motor Module*. When communication between the *Training Module* and the *Smart Motor Module* was established with a connection cable, it identified the *Smart*

[4]https://www.seeedstudio.com/Wio-Terminal-p-4509.html
[5]https://wiki.seeedstudio.com/Wio-Terminal-Battery-Chassis

Motors's name and allowed the *Training Module* to train or view the existing data. At the same time, the *Smart Motor Module* continued to run in *Playing* mode.



Figure 3.11: Welcome screen on the *Training Module* when *Smart Motor Module* is connected.

The user interface of the *Training Module* is shown in Figure 3.11. The rotary potentiometer on the connection PCB controlled the motor position. The circular blue button in the bottom right of the screen is a 5-way joystick. Left, right, up, and down buttons on the joystick were used to make selections of available options, and the button press executed the command or selected the option.



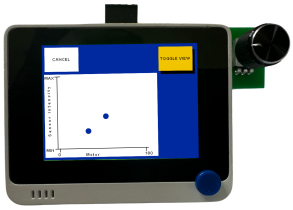
(a) Dashboard view of *Training* screen.



(b) Graph view of *Training* screen.



(c) Dashboard view of *Playing* or View screen.



(d) Graph view of *Playing* or View screen.

Figure 3.12: *Training* and *Playing* (or view) screen on *Training Modules* to visualize the data. The users can toggle between dashboard or graph view.

Figure 3.12 shows examples of the information displayed in the dashboard and graph mode for both *Training* and *Playing* modes. The users have options to toggle the view between the dashboard and graph view, add data points, delete data points, and test the training data on *Training* mode (Figures 3.12a and 3.12b). In *Playing* mode or View mode, they can visualize the training data and state of the sensors and motors in the dashboard and graph view (Figures 3.12c and 3.12d).

Bill of Materials

Table 3.3 shows the cost breakdown for a set of *Smart Motor* in 2022 and 2024 in US dollars (detailed cost breakdown in Tables A.1 and A.2). The cost per set of *Smart Motor* V2.2 was about $83 in both 2022 and 2024. Considering classroom usage, our assumption of one *Training Module* for six *Smart Motors Modules* averages the cost per Smart Motor set to about $28 in 2022 and about $33 in 2024.

Table 3.3: Bill of Materials for V2.2 version of *Smart Motors*

SN	Item	Cost in 2022	Cost in 2024
1	*Smart Motor Module*	$17.25	$23.34
2	*Training Module*	$65.71	$59.18
	Total	$82.96	$82.52

Feedback and reflections

We sent *Smart Motor* V2.2 to educators and designers in and outside the US for feedback. We also ran workshops with 3rd-5th grade students in a children's museum (2 hours) and 2nd and 3rd-grade students in a local school (6 hours over 3 days). In the museum workshop, we found a lot of users used the pre-existing training data and didn't retrain the motor [89]. Having pre-trained data allowed the users to test and build something quickly. However, in the second workshop, the users extensively used *Training Modules*. They used a *Training Module* to train the data, visualize the data, and explore other features, such as renaming the hub. Toward the end, each group wanted their own *Training Module* contrary to our assumption about the ratio of *Smart Motors* and *Training Modules* required in a classroom.

The flat surfaces of the *Smart Motor* Modules allowed the users to put *Smart Motor* in different orientations and attach building materials to them with tapes. Even when LEGO® pieces were provided, users preferred to use found materials. Young users and experts liked the shape, size, and overall form factor of the *Smart Motor*. The screen on the *Training Module* allowed the users to visualize tiny changes in the sensor readings and validate the data storage. In some instances, we noticed young users having difficulty connecting the modules and requiring help

from teachers to set them up.

Discussion

Smart Motor V2.2 validated our assumption that users want to save data on the *Smart Motor*, and some might prefer to use pre-existing data, which we will discuss in Chapter 4. It also showed the importance of having a screen for visualizing data and debugging. We found that having multiple parts increased the chances of failure and could divert teachers' time from supporting students' learning. We also needed to correct our assumptions about the ratio of *Training Modules* to *Smart Motor Modules*. Depending on the project, some users wanted to use the potentiometer to control the motors manually. Some users also wanted to frequently look at the data visualization to validate data storage and changes in sensor readings. As the only way for users to manually control the motors and visualize the data on V2.2 was on the *Training Module*, we would need more *Training Modules* in a classroom. This would significantly increase the cost of *Smart Motor*. Therefore, we decided to integrate the training and data visualization into the *Smart Motor* box in the next version.

We also gained insights about the buttons, connectors, and screen for the next iteration of *Smart Motors*. We had to be aware of materials that can be difficult to operate, like the connector latch from the *Smart Motor Module* to the *Training Module*. Similarly, the 5-way switch in the *Training Module* was confusing as it was small and didn't have the affordance of a joystick. So, we decided to use distinct buttons for specific purposes. The 2-inch X 2-inch X 2-inch form factor of the *Smart Motor Module* was compact enough to fit into different projects and was stable enough to support building on the top. This meant we needed to find a smaller screen to fit on the motor and to display all the relevant information to the user. A

smaller screen would mean we wouldn't be able to create a detailed user interface like the V2.1 and V2.2. So, we decided to come up with a more straightforward user interface. In the same vein, we decided to use icons instead of text to ensure the system could be used by children who couldn't read or understand English.

3.3.4 *Smart Motor* V3

With the feedback from V2.1 and V2.2, we built *Smart Motor* version 3 or V3 (Figure 3.13) in the summer of 2023. Two variations of V3 were made with discrete and continuous servo motors. We initially designed the housing with laser cut and 3D-printed parts to minimize the fabrication time but later updated the design as shown in Figure 3.13 with all 3D-printed parts.



Figure 3.13: Figure shows the isometric view of *Smart Motor* V3.

Design Features

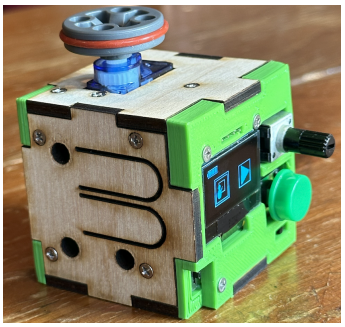
The *Smart Motor* hardware consists of a servo motor (discrete or continuous) connected to a Seeed Studio XIAO ESP32C3[6] microcontroller on a custom printed

[6]https://www.seeedstudio.com/Seeed-XIAO-ESP32C3-p-5431.html

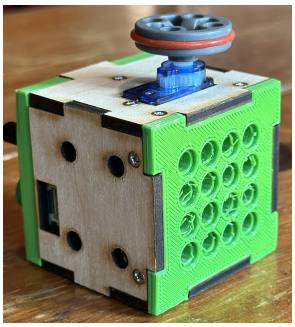
circuit board (PCB). The *Smart Motor* has a cubical form factor (1.85-inch X 1.85-inch X 1.85-inch) with either a mix of 3D-printed and laser-cut parts or all 3D-printed parts. Figure 3.14a shows the front face of the *Smart Motor* and has a *selection* button (*Selection*), a potentiometer (*Pot*), a power switch, along with a 0.96-inch monochrome OLED screen. On the left face, Figure 3.14b, are two navigation (*Nav*) buttons. The Grove-compatible sensor port is on the right face, and the USB-C port for programming and charging the battery is on the bottom face of the box. The Top face (Figure 3.14c) has a servo motor connected to a LEGO®-compatible wheel. The SM1 types have discrete servo motors where you can control the position, and the SM2 types have continuous ones where you can control the speed and direction of the motors. There are LEGO®-compatible holes for mounting LEGO® pieces on the box's left, right bottom, and back faces. The user interface on the *Smart Motor* box is called *standalone UI*.



(a) Front face of Smart Motor V3 with the screen, *Potentiometer*, and *Selection* button.



(b) The left face of Smart Motor V3 shows two *Nav* buttons.

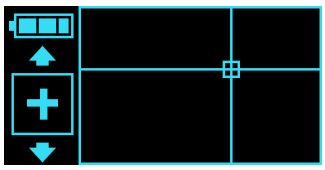


(c) Right and back faces of Smart Motor V3 with LEGO®-compatible holes and the motor on the top face.

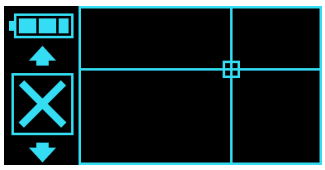
Figure 3.14: Figure showing different faces of a wooden *Smart Motors* V3 hardware.

The *standalone UI* uses icons to convey the information to the user instead of text. The potentiometer (*Pot*) on the front face controls the motor position (or speed), the *Nav* buttons on the side navigate different screens, and the *Selection*

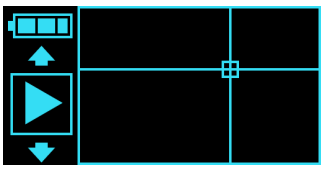
button is used as an action button. When the V3 is turned on, it starts on *Playing* screen (Figure 3.15c) if data is stored or on *Training* screen (Figure 3.15a) if no training data is saved on memory.



(a) *Training* screen, where users can add data points using the *selection* button.



(b) *Training* screen, where users can delete points using the *selection* button.



(c) *Playing* screen, where users can engage the *Play* mode and visualize the sensor readings and motor position.

Figure 3.15: Figure showing different options on the *standalone UI* on *Smart Motors* V3 .

Users can add or delete data on the *Training* screen. Figure 3.15a shows the add mode on the *Training* screen. The unfilled selection square on the screen shows the current value of the motor position on the Y-axis and the sensor reading on the X-axis. When the selection is made with the *selection* button on this mode, a filled square gets added (Figure 3.16), indicating that a data point is stored. The users can move the motor and choose a sensor reading to add another data point. There are no limits on the number and location of the filled squares in the current version of the *standalone UI*. Figure 3.15b shows the delete mode on the *Training* screen. When the *selection* button is pressed, the most recent data point is removed from the screen and memory.

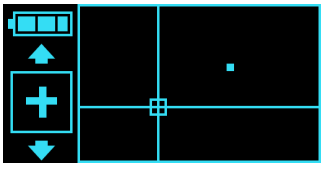


Figure 3.16: Figure showing training data stored with a dot on the screen.

When *selection* button is pressed on *Playing* screen, it engages play mode

(Figure 3.17). The screen color inverts to communicate that the play mode is activated. In this mode, the motor position or speed is determined by the machine learning algorithm using the training data set. The screen shows the current sensor value with the vertical line and the motor position with the horizontal line. Pressing *nav* buttons disengages the play mode.

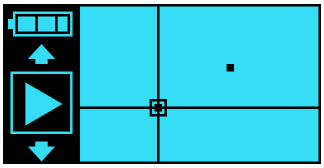


Figure 3.17: Figure showing play mode engaged on *Playing* screen.

Bill of Materials

Table 3.4 shows the detailed cost breakdown for one *Smart Motor* V3. The *Smart Motor* PCB unit cost depends on the fabrication company and the number of boards fabricated. In this case, 200 *Smart Motors* were assembled. It also depends on whether we order the PCBs with the components assembled. We have found that ordering PCBs with components pre-assembled reduces the overall cost by minimizing the assembly time and wastage of components. As shown in the table, with the overall cost of *Smart Motor* V3 being about $29.50, we achieved our goal of creating *Smart Motor* under $30.

Table 3.4: Bill of Materials for V3 version of *Smart Motors*

SN	Part	Component	Unit cost
1	*Smart Motor* PCB	CUSTOM	$16.42
2	Battery	Adafruit 4236	$6.95
3	Servo motor	Miuzei MG90S 9G	$2.76
4	Threaded inserts	M2 threaded insert	$0.09
5	Nut and Bolts	M2 6 and 12 mm	$0.18
6	Button caps	12 mm Tactile Switch cap	$0.13
7	Sensors	Grove light sensor	$1.37
8	Case	PLA filament	$1.50
	Total		$29.39

Feedback and reflections

Smart Motor V3 has been used with positive feedback in several workshops and events. It has also been used in a comprehensive usability study, which I will describe in the next chapter. The use in classroom settings has shown that the shape, size, and configuration of the buttons and sensors work together and do not hinder creatively using the *Smart Motor*. There was some feedback relating to the LEGO® compatibility of the V3 housing, referring to how it made it possible to build with LEGO® pieces but needed to be built with better tolerance so that pegs would stay in place. In addition to the LEGO® pieces, the blank surfaces on the V3 allow users to stick found materials to build projects.

Several adjustments were also made in V3. For example, in the first iteration, the power switches were small and difficult to operate, but they have now been replaced with larger switches. There was also feedback related to the user interface,

which underwent multiple iterations to the current version described above. To simplify the user interface, we removed features like saving multiple training data and added inverting the screen to communicate the activation of *Playing* mode. Users had difficulty discovering the laser-cut buttons on the side, which we first tried fixing by adding labels and then with the 3D-printed version with raised circles.

Discussion

The form factor of V3 was based on the *Smart Motor Module* of V2.2, where we combined the functionality of the *Training Module* and *Smart Motor Module* into one. Seeedstudio's Xiao ESP32C3 was the ideal microcontroller to replace the ESP8266 in V2.2 because it has a smaller footprint, more i/o pins, and a built-in charging circuit. The built-in battery allowed the users to move freely around the classroom and use the *Smart Motor* more creatively. We replaced the initial mix of laser-cut and 3D-printed parts design with an all 3D-print design in the final version of V3. This reduced the number of steps and time required to assemble, reducing the cost. With continuous improvements within V3, we have reduced assembly complexity, assembly time, and the number of parts required and increased robustness. We managed to do it while staying within the cost constraints of $30 per set of *Smart Motors*.

3.4 Discussion

Over the past three years, we have created multiple prototypes centered around trainable robotics. They all functioned based on the same principle—users providing training data that the system then utilized with a machine learning algorithm to generate output. They varied in cost, shape, and size, and users

interacted with them differently depending on the hardware. Along with the design intent, the other constant constraint was the cost, which determined the inclusion of hardware and features in each iteration.

Our development process followed the principles of standard engineering design [78]. We began with an idea and a set of constraints, which led to brainstorming several designs. We created multiple early prototypes using different hardware and user interfaces. The intended users then tested each prototype, and feedback was gathered from experts. We used the insights from the tests and feedback to create a list of requirements for the next iteration. With each iteration, we identified what worked and what didn't. We continued with the aspects that worked well, such as displaying data on the screen and the form factor of the *Smart Motor Module*. We made changes to things that didn't quite work, such as replacing the buttons with ergonomic ones, outsourcing the PCB fabrication, and updating the user interface to make it simpler. We also had to remove features that worked well in the earlier prototypes. For example, in V2.1, we had two training models (classification and linear regression), and in V2.2, we had two methods of data visualization (dashboard and graph). In V3, we retained only one training model (k-Nearest Neighbor) and graph view to visualize the data. We removed the two features to simplify the user experience with the available hardware (monochromatic 0.96-inch screen). By removing multiple steps to train and play with *Smart Motors* and limiting the number of operations users could perform, we aimed to minimize the error and shorten the learning curve. In addition, in our interaction with most users, they used graph view to make sense of the training data, current sensor reading, and motor position. Users could create a linear relationship between sensor reading and motor position for the training model by inputting multiple data points in a line. By removing these less used or redundant features, we were not

compromising the usability of the *Smart Motors*. But by removing or simplifying the options and adding features like combining training and data visualization into one unit, integrating LEGO®-compatible holes, incorporating built-in battery charging, enabling I2C sensors compatible sensor port, and including features like WiFi and BLE we lowered the barriers to entry and increased the ceiling of opportunities.

We encountered a few challenges along the way, such as travel restrictions and increased cost of goods during the pandemic. We regularly met with our collaborators and other stakeholders on Zoom to share ideas and updates. To get their feedback from hands-on experience, we shipped the prototypes at different stages of development, which presented challenges such as restrictions and delays in shipping, international taxes, etc. We were fortunate to find museum and STEM education experts ready to try out our preliminary designs and give feedback, which led to the eventual development of V3.

3.5 Conclusion

We envisioned an educational robotics kit that could be used in classrooms with low resources by students and teachers who want to include technology in their everyday learning but may not have the expertise or resources needed. With this robotics kit, users could robotize their projects and move things by simply training a motor instead of programming it. Using the engineering design process of identifying the problem, brainstorming the ideas, building and testing them, and refining and repeating this process, we have built *Smart Motor* V3. This standalone *Smart Motor* system can be used in a classroom to teach from robotics to arts and crafts and to introduce the concept of machine learning. We were able to build a trainable robotics kit for under USD $30. In the next chapter, I will discuss how we have

implemented different versions of *Smart Motors* in different settings. In Chapter 5, I will describe the usability test of *Smart Motor* V3, where I studied how users of different age groups interacted with the *Smart Motors* and how they engaged in a play-based open-ended activity.

Chapter 4

Implementation of *Smart Motors* in STEM classrooms

4.1 Introduction

We ran twelve workshops with *Smart Motors* in robotics camps in 6 schools, one museum, and one makerspace. Observing students and teachers using *Smart Motors* in classroom and workshop contexts was an integral part of the development of *Smart Motors.* The information and feedback from the students and teachers were crucial in setting the design constraint and adding or removing features to improve the designs and user interactions. In addition to getting feedback for the design process, we also gathered data on how the teachers used *Smart Motors* to teach various topics and how the students engaged with *Smart Motors* as novice users.

In this chapter, I will present three proof-of-concept studies from four workshops we have conducted over the years using the three prototypes described in Chapter 3. The four workshops were chosen for the study because they represented a wide range of students, from second graders to high schoolers and

from novices to students studying in a design class, and they used a wide variety of building materials as well as three different versions of *Smart Motors*. Through the analysis of the studies, I will discuss how the *Smart Motors* can be integrated into the classroom to support STEM education and what results emerge through this integration. I will highlight how *Smart Motors* can be used in classrooms to teach various topics and how, with minimal instructions, the students engage in self-directed learning, pushing the boundaries and challenging themselves with creative solutions.

First, I will present a study of a 5-day *Smart Motors* V2.1 workshop with middle school students in Nepal. Second, I will present a study of an arts and science investigation in an elementary school in the US using *Smart Motor* V2.2. Lastly, I will present the study of two Novel Engineering-based workshops with upper elementary and high school students from US schools using *Smart Motors* V3. I acknowledge that the *Smart Motors* used in the workshops differed, and the differences and distinct features in the versions might have resulted in some unique interactions. However, since the underlying principle of all the versions of *Smart Motors* was the same, the results I will discuss below would have been consistent regardless of the differences in hardware.

The workshops/studies presented below had video and audio data. Some workshops also had activity sheets as data. Further, the researchers present in the workshop took notes. For data analysis, the researchers consulted the notes and watched the videos, transcribing and noting important moments. The data were then used to analyze students' progression and understanding of STEM and the *Smart Motors* system through the design, build, and training process.

4.2 Acknowledgements

I want to acknowledge the teachers, administrators, and students who supported the workshops. I want to thank Simon Dahal, Adrienne Jacobson, Deborah Barolsky, Erin Glocke, William Church, and Kevin Lavigne for allowing me to use their classrooms, for running the workshops, and for collecting data. I also want to thank Olivia Tomassetti, Lydia Kresin, Aengus Kennedy, and Noah Saxenian for helping me build the prototypes and lessons and for supporting the workshops.

4.3 Study 1: Engineering Design with *Smart Motors* and Found Materials

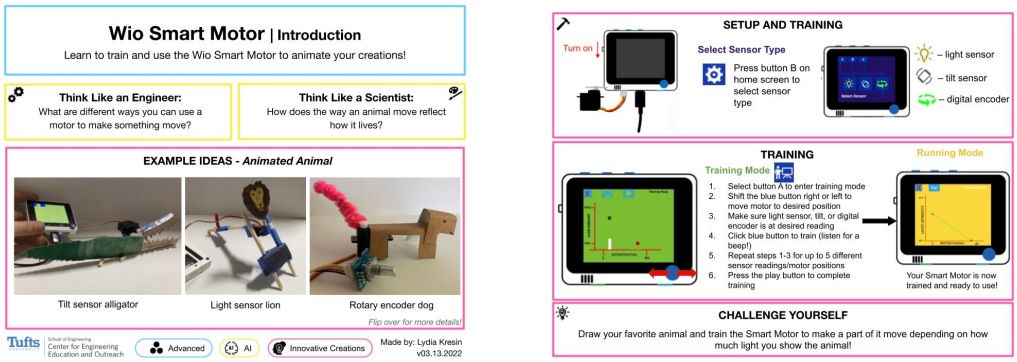
In July 2022, I ran a 5-day *Smart Motors* workshop in Nepal with 10 students from grades six to nine [90]. We used *Smart Motors* V2.1 and found materials like cardboard, scissors, paper, tape, colored pencils, and hot glue guns to build projects. V2.1 was a screen-based *Smart Motor*, one of the earliest prototypes. This workshop was designed to evaluate the effectiveness of *Smart Motors* in an engineering design workshop where the participants have little to no experience with robotics.

4.3.1 Workshop Details

The workshop was designed with five ordered activities to support participants to sequentially learn all the features of *Smart Motors* V2.1. The instructions were given using placemats [91]. Placemats allowed us to present the information while promoting solution diversity through self-exploration.

Day 1: Learn to train and use the Smart Motor to animate your creations!

Day 1's learning objective was to make the students able to train their *Smart Motors*. The prompt for the activity was to learn to train the *Smart Motor* and animate the creations. The instructor introduced the students to *Smart Motors* V2.1 and the training concept. Following the placemat's design principle [91], pictures of three example projects were given on the front page, as shown in Figure 4.1a. The back of the placemat showed instructions on how to train the *Smart Motor* (Figure 4.1b).



(a) Front page.

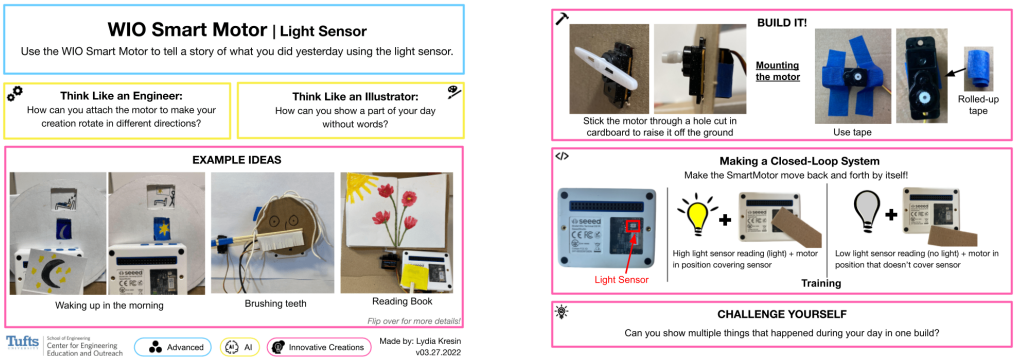
(b) Back page.

Figure 4.1: Figure showing placemat for Day 1 for Smart Motors V2.1 workshop.

Day 2: Use the Smart Motor to tell a story of what you did yesterday using the light sensor!

On Day 2, the learning objective was to make the student able to use the light sensor to train the *Smart Motor*. In this activity, the prompt was to use the onboard light sensor on V2.1 to train the motor and build and share an animated representation of an activity of their choice from their personal life. The front page on placemat (Figure 4.2a) showed examples of activities like waking up, brushing teeth, and reading a book to inspire the students to think about activities from their own lives. The back page, Figure 4.2b, shared ideas on the placement of the sensor and ways

to attach the motor to the cardboard using tape.



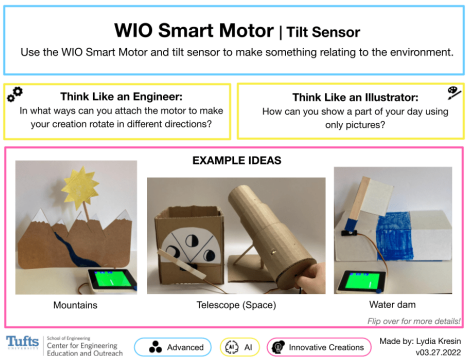
(a) Front page.

(b) Back page.

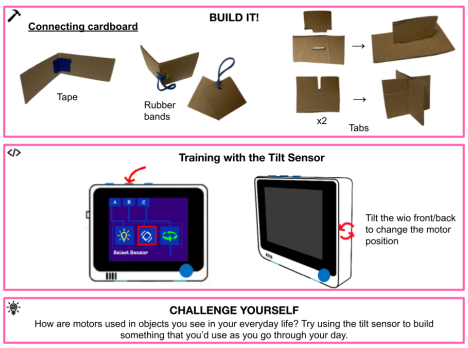
Figure 4.2: Figure showing placemat for Day 2 for Smart Motors V2.1 workshop.

Day 3: Use the Smart Motor and tilt sensor to make something related to the environment.

The prompt for the third day was to make something related to the environment and use the onboard tilt sensor to animate their build. The learning objective for this day was for the students to be able to use the tilt sensor to train the motor. The inspiration examples on the front page, Figure 4.3a, showed representations of a rising sun, phases of the moon, and a water dam. The back page, Figure 4.3b, showed ideas of connecting cardboard with different techniques to create complex structures.



(a) Front page.

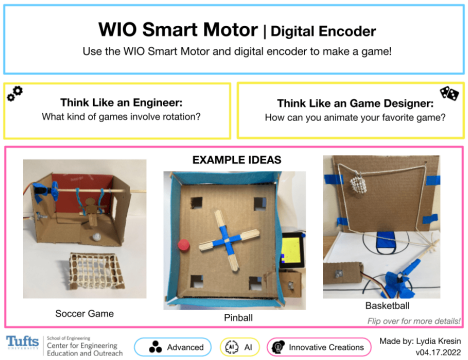


(b) Back page.

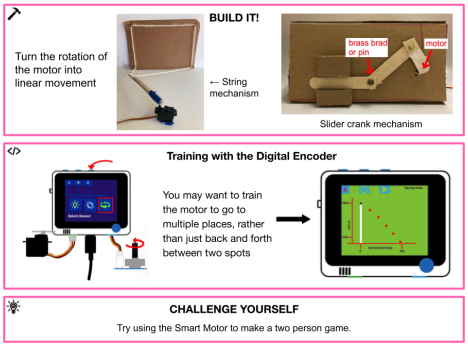
Figure 4.3: Figure showing placemat for Day 3 for Smart Motors V2.1 workshop.

Day 4: Use the Smart Motor and digital encoder to make a game!

On day 4, the students had to build a game with *Smart Motor* and a digital encoder as a sensor. Digital encoders were one of the three types of sensors that could be used on V2.1, and they had to be plugged into the *Smart Motor* using a cable. The learning objective for day 4 was for the students to use a digital encoder as a sensor to train the *Smart Motor*. The front page, Figure 4.4a, showed examples of projects representing soccer, pinball, and basketball for inspiration. The back page, Figure 4.4b, showed instructions on training multiple points and building mechanisms using strings and pins.



(a) Front page.

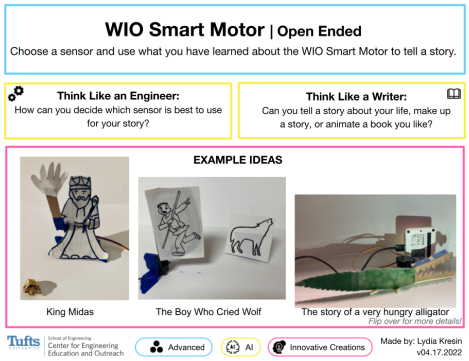


(b) Back page.

Figure 4.4: Figure showing placemat for Day 4 for Smart Motors V2.1 workshop.

Day 5: Choose a sensor and use what you have learned about Smart Motor to tell a story!

On the last day of the workshop, the student groups were asked to brainstorm a story they wanted to share through *Smart Motors*. The objective of this activity was for the students to use *Smart Motors* to tell a story they had read or composed. They were allowed to use any one of the available three sensors that would fit the storytelling. For inspiration, the front page showed examples of classic children's stories, such as King Midas and The Boy Who Cried Wolf (Figure 4.5a). The back page, Figure 4.5b, showed the idea of using either linear regression or the nearest neighbor algorithm on their data. It also showed the materials they had available to build their projects.



(a) Front page.



(b) Back page.

Figure 4.5: Figure showing placemat for day 5 for Smart Motors V2.1 workshop.

4.3.2 Results

The students voluntarily formed four groups of 2 or 3 on the first day according to their grades. Since none of the students had prior experience with robotics and only one student had some programming experience, all the students were starting at the same level. First, they were asked to explore the *Smart Motor* V2.1 and the features

using the placemat. The students looked hesitant and produced similar projects on the first day: an arm-like structure attached to the motor that moved side to side with the change in sensor. We also noticed that the older students worked better in groups by dividing and assigning tasks like building and training the motor. By the end of the hour, all groups had a trained *Smart Motor* and a structure that moved when the sensor was triggered.

On the second day, they continued working in their respective groups. Since they had already used *Smart Motors* the previous day, they could dedicate more time to building. There was significant solution diversity in the projects. One of the groups, group A, built an animation of a spoon picking up food from a plate to represent them eating their breakfast (Figure 4.6a). Another group, group B, built a head mount with cardboard sunglasses that would move up and down to cover the eyes based on the amount of light that fell on the sensor (Figure 4.6b). The third group, group C, built a fan to mimic how they used it to blow cold air, as the day before was unusually hot (Figure 4.6c). Group D used two *Smart Motors* to build a representation of a leg with two degrees of freedom kicking a ball. They used two motors to create two joins and trained them separately so they could control the novel precisely (Figure 4.6d). The projects' complexity on the second day was significantly higher than on the first.



(a) Group A recreated their morning breakfast with a plate of food with a spoon.

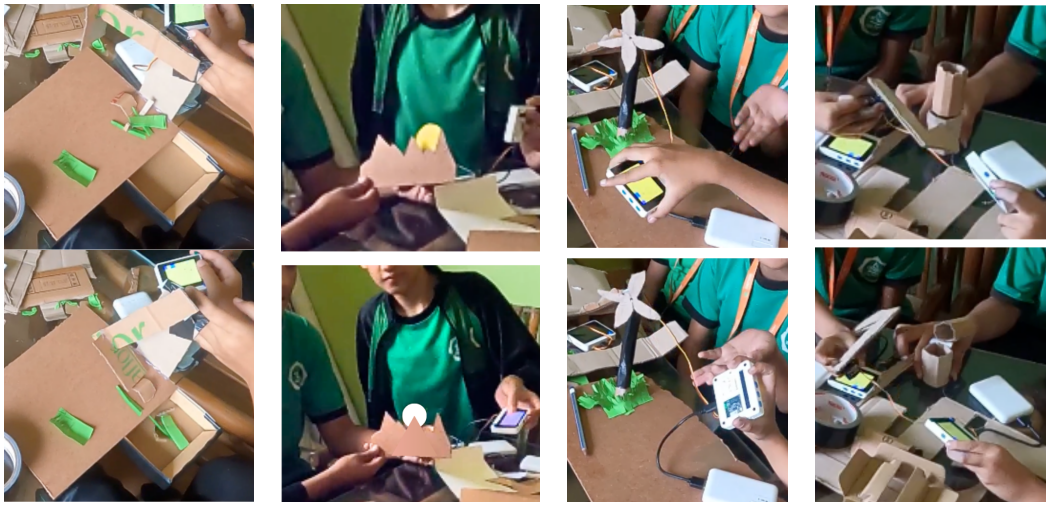
(b) Group B showed how they wore sunglasses when going out in the sun.

(c) Group C built a representation of a fan that blows cold air on a hot, sunny day.

(d) Group D used two *Smart Motors* to build a 2 DOF leg to kick a ball.

Figure 4.6: Projects from day 2 of workshop with *Smart Motors* V2.1.

On day 3, the students worked on environment-related projects. They created some personally meaningful contextual projects. Group A built an assistive sweeping device to clean up (Figure 4.7a). Group B built on the examples from the placemat and demonstrated an evening sky in which the sun sets on the horizon, and the moon rises when the earth rotates. They included the *Chandragiri* mountains near the school in this build (Figure 4.7b). The third group, group C, built a windmill replica to discuss renewable energy. They wanted the blades to run continuously but couldn't due to the limitation of the servo motor (Figure 4.7c). And finally, Group D discussed the prevalent issue of deforestation. They used a cardboard axe to swing with the sensor's tilt to knock over a cardboard tree. The group designed the tree to mimic breaking in half with the axe strike (Figure 4.7d). They said they wanted to add another *Smart Motor* to display the message "Save trees" when the tree fell but couldn't due to lack of time. The students were thinking about climate change, clean energy, and clean cities as environmental issues, and they used the builds as a storytelling tool.



(a) Group A's model of an automated sweeping machine.

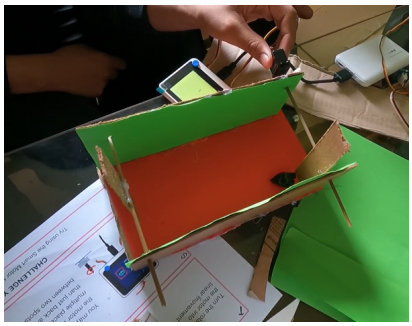
(b) Group B's representation of the sun setting over the horizon and the moon rising as the earth rotates.

(c) Group C's miniature replica of a windmill generating electricity.

(d) Group D's demonstration of an axe cutting down a tree.

Figure 4.7: Projects from day 3 of workshop with *Smart Motors* V2.1.

On day 4, we faced logistical challenges as we ran out of cardboard. The students had to reuse the cardboard and spent the bulk of their time trying to either negotiate with the other groups to exchange the materials or use what was available creatively. In the beginning, during the brainstorming session, students were enthusiastic and pitched numerous ideas to their groups. However, only two groups finished their projects on time. Group B tried building an air hockey-type game with two controllers but could only complete one in time (Figure 4.8a). Group C made a goalkeeper game, in which the objective for one player was to score a goal and for the other to move the goalie, controlled by the *Smart Motor* (Figure 4.8b). The other teams who could not complete their projects cited a lack of proper cardboard and glue guns. They also indicated they did not have enough time to realize their projects. It was noted that the groups who could not complete their projects had ambitious ideas and needed to put more effort into collaboration.



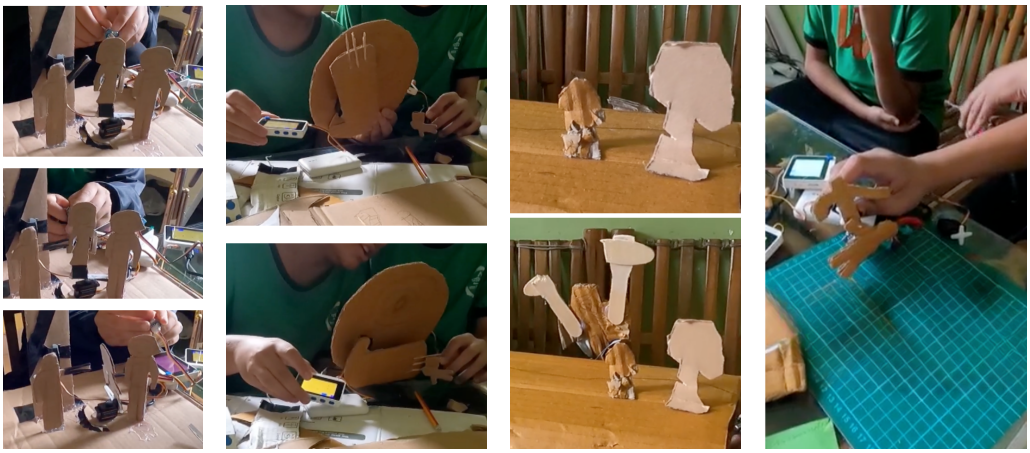
(a) Group B developed an air hockey-like game where players try to score by shooting the ball past the other player.



(b) In a goal-scoring game by Group C, one player throws Styrofoam balls to a goal post, and another blocks with a goalie using *Smart Motors*.

Figure 4.8: Projects from day 4 of workshop with *Smart Motors* V2.1.

On the final day of the workshop, we replenished the supplies. They were prompted to build a representation of a scene from a story they had heard or read. Group A retold the story of "This Ends With Us," with figures attached to two motors that swiveled and turned around to demonstrate how the events unfolded and how the characters moved on with their lives (Figure 4.9a). Group B developed a story-based project involving an adventurer who traveled to a village to fight a cave monster. They recreated a scene of the battle between the monster and the traveler (Figure 4.9b). Group C shared the famous Nepali story of a woodcutter. In short, the goddess who lives in a lake near the jungle is delighted by the honesty of the woodcutter and rewards him with gold and silver axes. The group recreated the scene where the goddess comes out of the lake to console the crying woodcutter after his wooden axe falls into the lake. The group attached the goddess to the motor to mimic her rising from the lake surface with the different axes as they told the story (Figure 4.9c). Group D told a short story about a miner who mined a diamond using a pickaxe.



(a) Group A's enactment of the story "This Ends With Us".

(b) Group B told a story of a traveler enacting a battle with a cave monster.

(c) Group C retold the children's story of a woodcutter and the goddess of the lake.

(d) Group D shared the story of a miner who could mine diamonds.

Figure 4.9: Projects from day 5 of workshop with *Smart Motors* V2.1.

4.3.3 Discussion

The workshop with *Smart Motors* V2.1 showed that *Smart Motors* can promote technical skills, critical thinking, creativity, and collaborative learning. I discuss the results by answering the two questions below.

How can Smart Motors be integrated into the classrooms to support STEM education?

During the workshop, the students demonstrated collaborative, critical thinking, and problem-solving skills, essential components of STEM education, by designing and executing their projects. Further, we observed that *Smart Motors* can be integrated into the classroom as tools for hands-on projects requiring minimal teacher intervention. Because the instructions to get started are minimal, the activities can be combined with placemats, enabling the students to independently navigate the system and get ideas for inspiration and discussion. This allows

teachers without prior robotics experience to effectively run these activities and focus on students' learning instead of worrying about technical issues irrelevant to the subject matter.

Smart Motors can support STEM education through hands-on projects to teach students essential robotics concepts such as sensing, processing, and actuation, as well as machine learning concepts like data collection and training. Building projects like the windmill replica and deforestation model can facilitate discussions about renewable energy and environmental conservation in an environmental science classroom.

In addition to STEM subjects, the final day's projects demonstrated how, with *Smart Motors*, students could recreate scenes from stories, helping them engage with literature and storytelling in a new, interactive way.

What results emerged through this integration?

Increased Complexity, Creativity, and Solution Diversity: Initially, projects were simple and similar, but as students became more comfortable with the *Smart Motors*, they developed more diverse and sophisticated solutions. By the second day, students showed significant solution diversity, indicating their willingness to push the boundaries of what they had initially learned, as shown in Figures 4.6, 4.7, 4.8 and 4.9. Over the five-day workshop, students showed a progression in the complexity and creativity of their projects by iteratively improving their projects and refining their designs based on the feedback and limitations they encountered.
Self-Directed Learning: Students were free to explore and experiment with the *Smart Motors* from the start. This encouraged them to think creatively and develop unique solutions to the prompts. They independently explored the features of *Smart Motors* and pushed the boundaries of the materials provided, indicating

self-directed learning.

Meaningful Projects: By the end of the workshop, students had created personally meaningful and contextually relevant projects, demonstrating their understanding of environmental issues and storytelling through their builds. Despite logistical challenges, such as running out of materials, students creatively used available resources and negotiated with other groups to complete their projects, demonstrating resilience and adaptability. The students were excited and proud of their creations.

Enhanced Collaboration: Students worked well in groups, dividing and assigning tasks amongst the group members. When the projects didn't work well, they reflected that they must acknowledge everyone's ideas and improve their collaborative skills. This collaborative environment helped them build more complex projects and think outside the box. Older students, in particular, showed effective collaboration by dividing and assigning tasks within their groups, which helped them manage more complex projects.

4.4 Study 2: Integration of *Smart Motors* in a Arts and Science Class

In December 2022, we ran a 3-day *Smart Motors* workshop with second and third-grade students in a makerspace classroom at a local private school where they used *Smart Motors* V2.2 and found materials like popsicle sticks, pencils, papers, pipe cleaners, brads, and tapes. As explained in Chapter 3, V2.2 had a detachable *Training Module* with a screen-based UI and a *Smart Motor Module* with the sensor and motor, which, when not plugged into the *Training Module* operated in *Play* mode. The lessons for this workshop were designed and delivered by the makerspace teacher, and I provided technical support and took notes.

4.4.1 Workshop Details

Their makerspace teacher, Ms. Anne (pseudonym), ran the workshop with her eleven second and third-grade students. She planned two lessons over three days and carried them out during her regular makerspace class hours. An assistant teacher supported her during the workshop, and the researchers took field notes and interacted minimally with the students.

Lesson 1: Drawing Bots

The goal of the first lesson was for the students to build Drawing Bots with *Smart Motors* and a light sensor. A few weeks before this lesson, as a makerspace activity, the students had built an Art Bot using a motor and colored pens. The motor on the Art Bot vibrated and moved due to an eccentric weight fixed on its shaft, dragging the pens attached to the contraption to draw random patterns on the paper. For this lesson, the students worked independently to explore the *Smart Motor* and build their Drawing Bots. Because the *Smart Motors* could run using the pre-trained data without the *Training Module*, they were initially not introduced to the idea of *training*. As the students got familiar with the technology and on a need-to-know basis, the *Training Module* was introduced to the students with which they would modify the behavior of the motor. In terms of materials, they were allowed to use five popsicle sticks to build the arm, pipe cleaners and brads to build the hinge, tape, foam stickers to attach the arm to the motor, and a pencil and paper to draw. The students created drawings on A3-sized papers. Placemats shown in Figure 4.10a and Figure 4.10b were used as reference materials.



(a) Front page. (b) Back page.

Figure 4.10: Figure showing placemat for Lesson 1 for *Smart Motors* V2.2 workshop.

The students worked independently. They started the workshop by first exploring the *Smart Motor Module* and identifying different parts: *Smart Motor Module*, sensor, and battery pack, and writing their answers in their activity sheets shown in Figures B.1a and B.1b. In the end, they were asked to answer the reflection questions shown in Figure B.1c.

Lesson 2: Conductor and Insulator Dashboard

In the second lesson, the students explored the resistive properties of different materials they were given using a custom *probe sensor*. A probe sensor was a voltage divider circuit that measured voltage drop across the two probes, indicating the material's resistance as shown in Figure 4.11. The students had to build a dashboard on paper and use the *Smart Motor* to point to different labels to classify objects based on their resistance. For this activity, they needed to train the motor to move to multiple positions using the *Training Module*. The teacher prepared step-by-step instructions for the students on the activity sheet (Figure B.2).

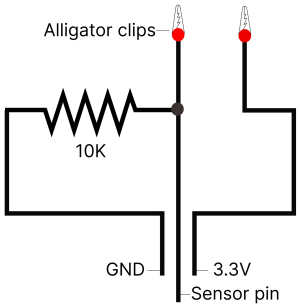


Figure 4.11: Schematic of the probe sensor shows a voltage divider circuit to measure the voltage drop across the alligator clips.

4.4.2 Results

The two lessons were conducted in three days: Lesson 1 during class duration (1 hour 15 minutes) on December 6th and December 9th (about an hour), and Lesson 2 during the second half of December 9th and December 13th. I will divide and present the results according to the activities' days.

Day 1: Drawing Bot

During the first day of the workshop on December 6th, the students observed Ms. Anne's demonstration of *Smart Motors* before getting hands-on experience with the materials. Ms. Anne showcased the *Smart Motor Module* and a light sensor attached to it and manipulated the motor's movement by covering and uncovering the light sensor as she moved around the room. Following the demonstration, the students spent approximately 5 minutes individually exploring the *Smart Motors* and completing activity sheets (Figure 4.12). When asked about their observations, the students shared insights on what caused the motor to move. Some noted that the movement was triggered by closing and opening the grip around the sensor, while others observed that plugging and unplugging the sensor caused the motor

to move. There was also a discussion about whether the sensor was sensing touch, and students speculated that pressing or touching the sensor could have caused the motor to move. Ultimately, the class concluded that the motor's movement was caused by the amount of light falling on the sensor, confirming that it was indeed a light sensor.

When the teacher asked the students for their understanding of what a sensor is, one student explained that a sensor senses; for example, a light sensor detects the amount of light, while another student added that fire detectors sense fire by detecting smoke and steam. Furthermore, one student shared their experience with a robot they owned that could sense objects. Here are some excerpts from the students' activity sheets:

1. *When you touch the light sensor, it moves at a 150-170 degree angle.*
2. *When you touch the little blue thing, it starts to move. It kind of moves.*
3. *It turns 90 degrees both clockwise and counterclockwise.*
4. *If pressed lightly, it moved!*



(a) Group 1. (b) Group 2. (c) Group 3. (d) Group 4.

Figure 4.12: Students exploring the *Smart Motors* and light sensors and writing their observations.

Ms. Anne then demonstrated a Drawing Bot she had built with a Popsicle stick,

foam pad, and a pencil (Figure 4.13). When the light sensor was covered, the motor would move and swing the stick in an arc, and the pencil attached to the end of it would trace a curve on the paper underneath. The students said they could draw a rainbow or a sunset with this setup. The instructor instructed the students to use Popsicle sticks and foam pieces with pre-made holes for pencils, tapes, and other materials in their bins to build their own Drawing Bots. She also informed them to refer to the placemats for further building instructions.

Student 1: *How can we make it different than what you have?*

Instructor: *You could try changing the angle of the arm.*

Student 2: *You could make it branch off and have multiple pencils attached.*

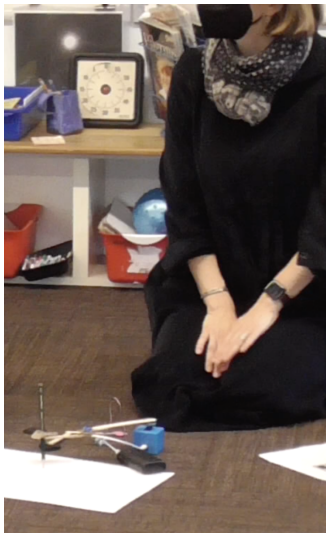


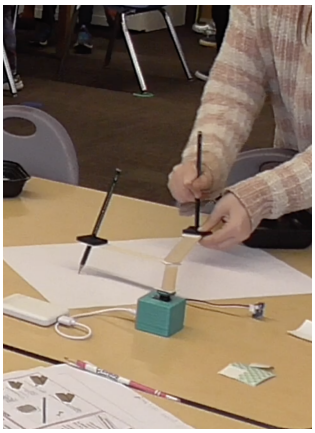
Figure 4.13: Picture of Ms. Anne demonstrating the Drawing Bot and introducing the lesson's goal to the class.

The students collected the materials and the placemats to refer to for building instructions. Students quickly made hinges and used foam stickers to attach the arm on the *Smart Motor* and a pencil on the other end with a foam piece. Most of the students' first designs resembled what Ms. Anne had demonstrated (Figure 4.14a).

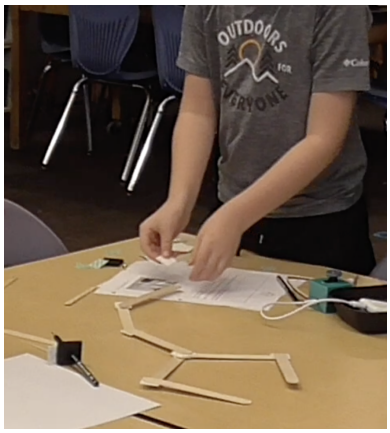
Mira (pseudonym) first played with a pencil and colored pens and then built a two-armed design, as shown in Figure 4.14b. Ms. Anne asked Mira to demonstrate her creation to the group and asked if she wanted to change how the *Smart Motor* was drawing. Mira said she would like to be able to control the angle at which the motor moved so she could draw arcs of different lengths. Ms. Anne asked another student, Carl (pseudonym), what he would like to change in his current design; Carl said he would want to control ”the variable” to control how much it turns, give it multiple pencils, and maybe add a hinge. Students told the teacher they also considered designing with hinges and multiple pencils. During the demonstration, one of the students correctly noticed that the motors were moving differently. This was because they were trained with different training data. The students continued building, and some of them, like Sam (pseudonym) in Figure 4.14c, were pushing the limits of the Drawing Bots with their designs.



(a) Mira’s first attempt at a Drawing Bot with a blue pen.



(b) Mira added two pencils to see how that changed the patterns the bot created.



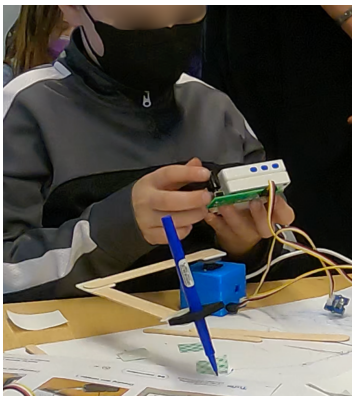
(c) Sam pushed the limit of the Drawing Bot with this interesting design.

Figure 4.14: Students creating artwork and experimenting with the design of their Drawing Bots.

After playing with their Drawing Bots for about 10 minutes, Ms. Anne demonstrated the *Training Module*. She informed the students they could read the

light sensor reading with the red line on the screen and turn the motor to a position of their choice using the potentiometer. She then showed how to add pairings of the motor positions for different light conditions on the *Training Module*. She asked the students to return to their building tables and think about how they would want their motors to move. She walked around with the *Training Module* to help the students learn how to use it. Carl quickly learned how to train the motor with a little help from the teacher (Figure 4.15a). He also helped his classmates use it (Figure 4.15b). One more student, Mira, got to play with the *Training Module* before the end of day 1 (Figure 4.15c). However, it was unclear from the video data if she could train her motor.

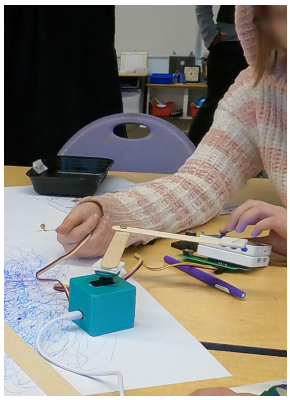
For final reflections for day 1, Carl said he could train three points so his motor could move to three positions, giving him more control. Another student said they wanted to always attach the *Training Module* to the *Smart Motor Module* so they could precisely control the motor with the potentiometer. Students shared how they built hinges to randomize the movements, hooked the sensor to the chair, and controlled the motor by rocking it. Talking about the benefits of the Drawing Bot, one of the students shared, "*You have to build it once, and it can keep drawing it! Unless it breaks!*"



(a) Carl interacted with *Training Module* to learn how to train the *Smart Motor*.



(b) Carl helped Liz train her *Smart Motor*.



(c) Mira experimenting with the *Training Module.*

Figure 4.15: Students learning how to use *Training Module* to train their *Smart Motors*

Day 2: Drawing Bot and Conductor and Insulator Dashboard

On the second day of the workshop, December 9th, Ms. Anne asked the students to think back to what they had done on Tuesday. She wanted them to reflect and compare their Drawing Bots with the Art Bot, a contraption they had built a few weeks earlier using a motor with an eccentric shaft, and fill out the activity sheet (Figure B.1c). While discussing the differences between the bots, they noted that with the Drawing Bot, the user had precise control using the light sensor, while the Art Bot had limited control with only a power switch. Furthermore, the Art Bot's motor relied on continuous rotation, whereas the Drawing Bot could only sweep half a rotation. One student also mentioned that the Drawing Bot could be trained, but the Art Bot could not. On that note, Ms. Anne said everyone would get a chance to use *Training Module* to train their Drawing Bot on day 2.

The students spent most of the time exploring the *Training Module* to train their Drawing Bots and working on their drawings. One of the students used the potentiometer on the *Training Module* to precisely control the motor movement and

draw arcs. Another student, Eric (pseudonym), known for being energetic and hard to contain, focused intensely on exploring the *Training Module* and its features. He discovered how to rename the *Smart Motor Modules* and offered to rename it for other students. He also discovered a bug that allowed him to clear the graph on the screen by precisely moving the potentiometer and controlling the amount of light falling on the light sensor. He trained his motor to move linearly proportional to the amount of light falling on the light sensor. Figure 4.16 shows the training data he had taken on his *Training Module*.

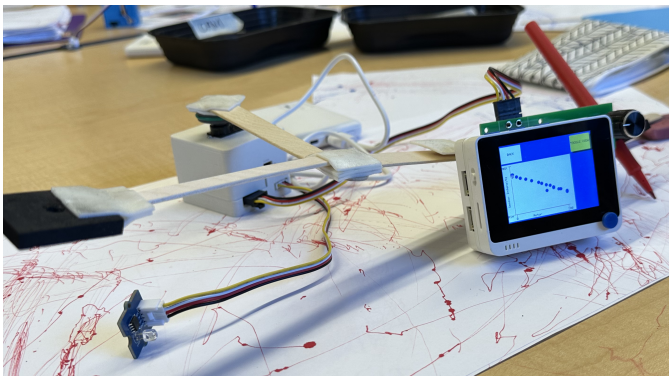


Figure 4.16: Screen showing Eric's training data on *Training Module*.

The students controlled their Drawing Bots in different ways. Some used the pre-trained data, so they didn't use the *Training Module*, some trained their motors, and others used the tethered *Training Module* to directly control the motors (Figure 4.17). In Figure 4.17a, Rumi (pseudonym), on the left, had her motor trained for two positions, while Monika (pseudonym), on the right, did not train the motor. Monika, when asked why she didn't train her motor, said she didn't have one available to learn and use. Both Rumi and Monika had multiple colored pens attached to their Drawing Bots. Monika's final artwork is shown in Figure 4.18. Some students, like Aiden, used the *Training Module*'s potentiometer to precisely move the pen to draw (Figure 4.17b).



(a) Rumi and Monika created artwork with their Drawing Bots with multi-colored pens.

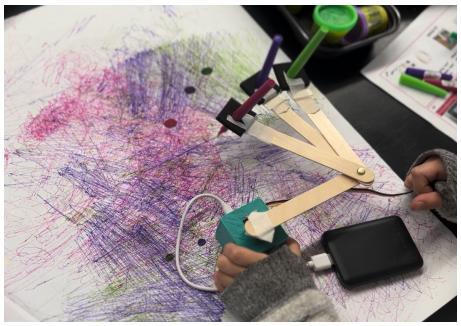


(b) Aiden used the tethered *Training Module* to control the Drawing Bot.

Figure 4.17: Representative images of different ways students controlled their Drawing Bots.



(a) Monika's Drawing Bot's position when light is uncovered.



(b) Monika's Drawing Bot's position when light is covered.

Figure 4.18: Figure depicting how Monika used three colored pens to create the pattern.

In the remaining 10 minutes of the second day, Ms. Anne demonstrated the *probes sensors* and introduced the prompt for Lesson 2. She showed how touching a ball of Play-Doh made the motor swing in one direction, and touching the rug made it move in the opposite direction. One student quickly guessed that this had to do with the flow of electricity. For students who were satisfied with their Drawing Bots, she offered they could start working on a dashboard on a piece of paper indicating where the motor would land when the probes touched different objects following

the instructions on the activity sheet (Figure B.1c). Some students started to explore the probe sensor and test different things like Play-Doh and graphite in the time remaining.

Day 3: Conductor and Insulator Dashboard

December 13th was the third and final day of the workshop. Ms. Anne began the class with a video from *www.openai.org* about training a robotic arm to solve a Rubik's cube. The students reflected on the video and discussed how they could solve a Rubik's cube using *Smart Motors*. Carl remarked that fully automatic could take at least 18 years, but using *Smart Motors* and controlling it with the light sensors might make it possible to do it in a month. Another student drew a parallel between the video and *Smart Motors*, noting that both systems used sensors to provide input to a computer.

Then, Ms. Anne demonstrated how to train the *Training Module* and build a dashboard (Figure 4.19). The students seem to remember how to use the *Training Module* from the previous class. On her dashboard, she had labels for insulators and conductors, some resistance and more resistance. A student looking at the dashboard had a question.

Student 1: *What is the difference between a resistor and an insulator?*

Teacher: *Does anyone have an idea?*

Student 2: *A resistor prevents too much electricity from passing through it, and an insulator prevents electricity from passing through it, or if it starts in it, it doesn't let it go out.*

Student 1: *And what is some resistance?*

Teacher: *It means some electricity goes through but resists a bit.*

Student 1: *What is the difference between some resistance and more resistance?*

Teacher: *It means it will resist more electricity.*

They also discussed why the probes sensed no resistance when touching each other. Carl observed that because the probes were made of metals, which are conductive, they must show no resistance.



Figure 4.19: Figure showing Ms. Anne demonstrating how to measure an object's resistance using the probe sensor.

Some students started building the Conductor and Insulator Dashboard in their previous class. On day 3, they trained the motor to go to the labels to show the property of the material they were testing. They tested with materials they could find in the classroom, like graphite, paper clips, furniture, skin, nails, and hair. Additionally, some students experimented with making long, thin threads of Play-Doh to see how it changed the resistance and affected the motor's movement. They discovered the resistance increased by making it longer and thinner (Figure 4.20).

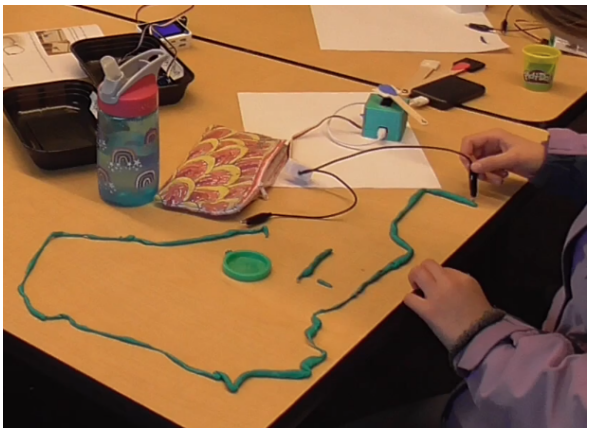


Figure 4.20: Figure showing a student's experiment with the length and thickness of Play-Doh and its resistance.

Students built dashboards to identify the conductive properties of materials. For example, Monika built a dashboard with labels for insulators, resistors, some resistance, and conductors. She tested a pencil, which showed that it was an insulator (Figure 4.22a). Another student suggested that the graphite on the pencil might be conductive, which she tested next and found that it was conductive. She also tested Play-Doh (Figure 4.22b) and metal (Figure 4.22c).

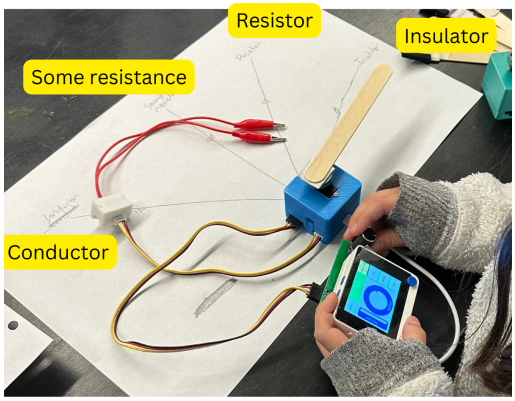
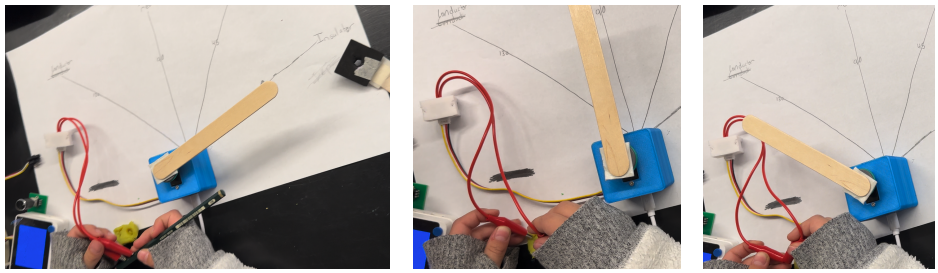


Figure 4.21: Figure showing Monika's Conductor and Insulator Dashboard.



(a) The pencil's conductivity test shows an insulator.

(b) Play-Doh's conductivity test shows some resistance.

(c) Metal's conductivity test shows a conductor.

Figure 4.22: Monika tests different materials on her dashboard.

In the end, the students shared what they learned: Play-Doh and humans are conductive, but their nails and hair are not. Metals, graphite, and smudged graphite on paper are also conductive, but only over short distances. They also learned how to train their robots. The workshop concluded with students filling out their reflection sheets.

4.4.3 Discussion

The workshop with *Smart Motors* V2.2 showed that the ease of use and versatility of *Smart Motors* allowed for use in classrooms for arts-related and science investigation lessons. It can be a valuable tool in STEM education, bridging the gap between technology and pedagogy.

How can Smart Motors be integrated into the classrooms to support STEM education?

Smart Motors are not difficult to learn and operate, as shown by how quickly the second and third graders learned to use it and use it in interesting and creative ways. Ms. Anne and I met once a few weeks before the workshop to discuss how she could use *Smart Motors* with her students in her makerspace class. I

gave her a demonstration of *Smart Motors* and showed her the activities we had done in the past with light sensors. Ms. Anne wanted her students to do activities related to art and creativity with *Smart Motors* with the theme "things that move". We brainstormed ideas like getting the students to read a poem and expressing the poem using *Smart Motors*, similar to a Novel Engineering activity where students read a story or a novel to create solutions for the characters. Another idea was for the students to build kinetic sculptures using *Smart Motors*. In addition, she wanted to do some science-related activities with the students. After brainstorming and learning about her curriculum requirements, I built and demonstrated a probe from *Smart Motors* that could measure the resistance of materials. When we talked in a few weeks, Ms. Anne had designed two lessons, prepared the materials, and was ready to execute them with her second and third graders. She had designed engaging activities that effectively blended arts and sciences and met the curricular requirements for her second and third-graders. The two lessons indicate that teachers can use them in various ways to engage students in creative activities.

Smart Motors are versatile tools that can be used to design fun, hands-on STEM activities. In the first activity, the students built structures to create artwork. They went through an iterative building, testing, and improving process - the engineering design process. They also learned and applied the knowledge of sensors and actuators, building blocks of robotics. Additionally, observations from the workshop indicated that even young students could grasp the concept of training a robot, laying a foundation for introducing more advanced concepts like Artificial Intelligence and Machine Learning in future lessons. Playing with the *Smart Motors* paved the way for the teacher to discuss topics of AI with the second and third graders.

In the second lesson, Ms. Anne used *Smart Motors* as a tool to engage the

students in hands-on activities to investigate insulators and conductors. This activity can be modified with the appropriate sensors to investigate other material properties like colors, temperature, reflectivity, mass, weight, etc. In both lessons, there was plenty of discussion around math concepts like angles, length of arcs, radius of circles, and geometrical shapes. Activities can be designed around such concepts to facilitate in-depth discussions and provide practical examples.

Notably, the workshop operated entirely without computers, highlighting the simplicity and reliability of *Smart Motors* in facilitating a fun and engaging robotics experience.

What results emerged through this integration?

Solution Diversity: The students followed different paths to create the Drawing Bots. The tool allowed them to express themselves in different ways and paved the way for diverse solutions. Rumi, Monika, Aiden, Carl, Mira, and other students had different solutions to achieve the lesson goals.

Engaging: All the students were highly engaged in building, sharing, and asking questions during the workshop. This was mostly noticeable with Eric, who had difficulty focussing on activities but was intrigued by the *Smart Motors* and its capabilities. He was asking questions with his friends and helping them with their issues. He was engaged through the workshop.

Low Risk of Failure: The *Smart Motors* worked out of the box as they were pre-trained. Even students who wanted the motor to behave differently could use the potentiometer to control the motor. The requirements for success, as well as the risk of failure, were hence pretty low. The students started with something that worked quickly and iterated several times to advanced designs. The comfort of knowing they have something to fall back on probably enabled them to try out

complex designs and hence gave them creative freedom to express their knowledge.

Rich Discussions: Throughout the workshop, the teacher engaged the students to discuss what they observed and noticed. The students provided rich discussions about the sensors, angles, shapes the bot created, and properties of materials. They compared the Art Bots with their Drawing Bots and gave insightful reflections.

Creativity and Collaboration: The students created creative solutions for the prompts. Some employed innovative ways of triggering the light sensor, like rocking the chair to cast shadows on the sensor. Some used the momentum of the motor arm to create random and interesting patterns. Even though they worked individually, they collaborated by sharing ideas and supporting each other in effectively understanding and using the technology.

Bridging Theory with Practice: The workshop underscored the effectiveness of *Smart Motors* in bridging theoretical concepts with practical, real-world applications by making concepts like resistance, conductor, and insulator tangible and hands-on.

4.5 Study 3: *Smart Motors* in play-based engineering design workshops

In this section, I will present the results from two workshops we did with elementary and high school students using *Smart Motors* V3. First, I will describe the details of the workshops and present the results. Based on the findings, I will discuss how *Smart Motors* can be integrated into STEM classrooms and what results can emerge from this integration. Then, I will present my analysis of the trends in the states of play in those two workshops using the Learning through Play Experience Tool for few selected students. The play trends will help us characterize the students' experience of plays when we integrated *Smart Motors* in play-based engineering design workshops.

4.5.1 Workshop Details

The first workshop, Workshop 1, was conducted in June 2023 at a robotics camp with twelve fourth through sixth graders. The second workshop, Workshop 2, involved ten high school seniors and was conducted at a high school in November 2023. We developed a three-session play-based activity for the workshops to introduce and implement *Smart Motors* V3. Two different educators, both with extensive experience in formal and informal education settings, led the two workshops. Workshop 1 was part of a larger 5-day robotics camp at a local makerspace in New Hampshire. In the camp, students learned to use tools like Scratch and LEGO® SPIKE™ Prime. Workshop 1 was conducted on day 2 of the camp and consisted of two and a half hours of instructional time. Ten participants from the camp volunteered for the workshop, and data were collected from nine consenting participants. Workshop 2 was held in a Chemistry and Physics Projects for Seniors (CAPPS) course at a high school in New Hampshire. Eight participants consented to data collection. Workshop 2 was conducted in two days, with 60 minutes of activities per day of instructional time. The sessions included activities such as identifying patterns using visual aids of animals, training *Smart Motors*, and engaging in an engineering activity with *Smart Motors*.

Activity 1: Introduction to AI and ML and Hello World Activity with Smart Motors

The first activity had two sessions, first to introduce the students to the concepts of Artificial Intelligence (AI) and Machine Learning (ML) and second to implement *Smart Motors* as a practical application of ML. In the first session, the instructors introduced the students' concepts of AI and ML through discussions and activities. The instructor discussed with the students how ML functions by recognizing patterns and making informed decisions, mirroring human cognitive processes.

Visual aids, such as images of animals (dogs, cats, tigers, and wolves), were used to engage students in identifying patterns. The class examined these animals' physical attributes, discussing how they could recognize and categorize them using prior knowledge. This activity helped students draw parallels between human and machine learning processes, emphasizing the role of data and training algorithms.

The second session was a hands-on experience with *Smart Motors*. It provided students with a practical application of AI and ML using *Smart Motors*. The session began with a presentation and demonstration of *Smart Motor* features and functionalities. Students were tasked with building a "Hello World" waving mechanism using LEGO® pieces and *Smart Motors*. They learned to train the motors to perform tasks using a light sensor without traditional computer programming. Working in groups and individually, the students explored the *Smart Motor* interface and trained the motors to make the LEGO® arm wave. Assistants were available to help with any issues. At the end of the session, students shared their builds, showcasing their understanding and creativity.

Activity 2: Novel Engineering with Smart Motors

The second activity of the workshop was an hour-long Novel Engineering activity based on Candace Fleming's story "Muncha! Muncha! Muncha!" The Novel Engineering framework involves reading a story, discussing the issues and challenges faced by the characters, and designing solutions for those characters [88]. In this session, the students listened to the story about Mr. McGreely, a farmer troubled by bunnies stealing vegetables from his garden.

After reading the story, the instructor asked the students to choose a character they connected with—either Mr. McGreely or the hungry bunnies—and identify the problems faced by that character. The students worked in groups to design

solutions, using building pieces from the LEGO® SPIKE™ Prime kit without the sensors, motors, and hub. The session concluded with each group sharing their designs and explaining the rationale behind their solutions. This activity encouraged students to apply engineering principles to solve real-world problems creatively and collaboratively.

Notable differences in two workshops

While the two workshops shared the same content and playful approach, they differed slightly due to the age groups and settings. Workshop 1 was conducted with elementary students (fourth through sixth graders), and Workshop 2 was with high school seniors.

In Workshop 1, the Smart Motor code included features for saving and retrieving multiple training datasets, adding complexity to the user interface (UI) (as described in Chapter 3). For Workshop 2, the firmware was updated to simplify the UI. The duration of activities also differed: Workshop 1, part of a camp, had longer building times, with sessions two and three lasting one hour each. In contrast, Workshop 2, conducted during high school class hours, had 30 minutes for session two and 45 minutes for session three.

Additionally, Workshop 1 participants used position control (SM1 type) *Smart Motors*, whereas Workshop 2 participants used both position control (SM1 type) and speed control (SM2 type) *Smart Motors*. A position control or SM1 type *Smart Motor* uses a discrete servo motor, and the users can select the positions of the motor as the desired output. A speed control or SM2 type *Smart Motor* uses a continuous servo motor where the users can use the direction and speed of the motor as the desired output.

4.5.2 Results

I describe the results for each session separately. As described above, Activity 1 had two sessions: Introduction to AI and ML and Hello World Activity with *Smart Motors*, and the third session was in Activity 2: Novel Engineering with *Smart Motors*.

Session 1: Introduction to AI and ML

In session 1, the instructors started the discussion by showing a picture of a dog and asking the students if it was a cat or a dog. Unsurprisingly, the students identified it as a dog in both workshops. In Workshop 1, one student said, "*We know the pattern of a dog... they usually have a longer snout, and they have a different foot shape*" as their reasoning. In Workshop 2, the reasons were, "*it has a long face like other dogs I've seen.*", "*It is large and pretty tall with long legs*" and *"Looks like a lot of dogs I have seen in the past"*.

Next, when the instructor showed the picture of a cat, the students again correctly identified it as a cat. One student from Workshop 1 reasoned, "*I know a cat that looks just like it*.". Another student chimed, "*Cause of how it is standing. How it looks, and it has smaller feet than a dog does. And it is smaller*." Similarly, in Workshop 2, students observed the whiskers, shorter snout, paws, puffy hair, and a long tail.

The instructor then showed a picture of a tiger and asked the students to classify it as a dog or a cat. The students immediately said it was a cat. The Workshop 1 instructor challenged, "*But you said cats have smaller features than dogs, but this is larger than dogs.*" To which one of the students corrected, "*Some cats are smaller*.". Others noticed the similar face shape as a cat, retractable claws, similar

nose structure, and whiskers. In Workshop 2, the students had similar reasonings, including shorter snout, long tail, and patterned fur. Next, the students correctly classified the next animal, a wolf, into a dog category.

The final picture the instructor showed was a hyena, and students were divided because it had features of a cat and a dog. The instructor discussed how we recognize and classify objects using prior knowledge and information and how we sometimes cannot categorize objects because we don't have enough information. They drew parallels between humans and machines and discussed how machine learning uses large amounts of data to train a model, which is then used to make predictions later. They segued the discussion into the introduction of *Smart Motors*.

Session 2: Hello World Activity with Smart Motors

In session 2, the instructors introduced the *Smart Motors* as a robotics tool that works by training instead of programming to get the desired outcome. They demonstrated how to train the *Smart Motors* with a light sensor and asked the students to build a hand using LEGO® pieces that waved using a light sensor (Figure 4.23).

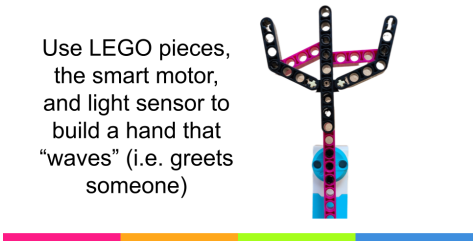
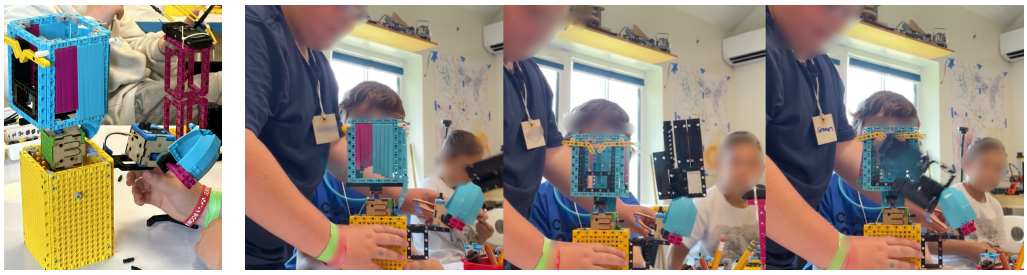


Figure 4.23: Figure showing the prompt for "Hello World" activity with *Smart Motors* V3.

The students in both workshops worked without much support or instruction from the instructor. In Workshop 2, everyone learned how to train from the

instructor's demonstration. In Workshop 1, at least one student in each group learned how to train the motor early by asking the instructor or figuring it out independently, and they could help their group mates. The common trajectory in both workshops was to build something simple, out-of-the-box, or complex next. In workshop 2, around halfway time, they were encouraged to try the SM2 type *Smart Motor*. So, many students built two designs: one with SM1 and another with SM2.

Dan, Will, and Ben (pseudonyms) from group 1 worked as a group to build a humanoid (Figure 4.24). Ben learned to train the Smart Motors early on and helped Dan and Will train their motors. They divided the task into building the head, arms, and body and trained their motors separately.



(a) Close-up image of the project.

(b) Different stages of the waving humanoid.

Figure 4.24: Dan, Will, and Ben from Workshop 1 show off the humanoid project for activity 1.

Groups 2 and 3 were similar in many ways. Brad (pseudonym) from group 2 and Max (pseudonym) from group 3 figured out how to use the *Smart Motor* early. They could help Leo (pseudonym) and Ava (pseudonym) from their groups when they asked for assistance. Brad first built a waving arm and experimented with a box to hold his arm, which didn't quite work out. Max experimented and built a claw that could grab onto objects and pick them up. Leo and Ava explored the motors on their own before asking for help. Then Leo spent most of his time perfecting his arm, focusing on the details, and figuring out the training towards the end when he

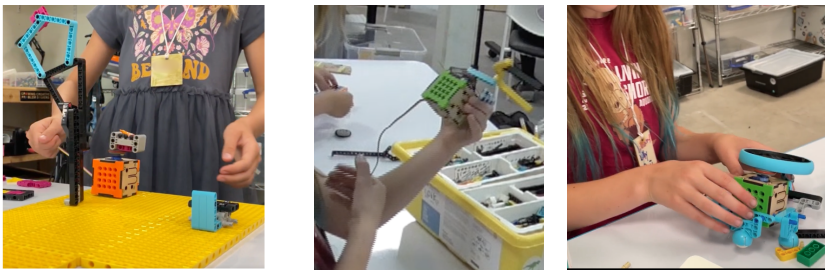
lost his data. Figures 4.25a and 4.25b show Brad's and Leo's builds, and Figures 4.25c and 4.25d show Max's and Ava's builds.



(a) Brad's build. (b) Leo's build. (c) Max's build. (d) Avas's build.

Figure 4.25: Figures showing waving mechanism from groups 2 and 3 for activity 1 from Workshop 1.

Laura and Rose (pseudonyms) in group 4 had similar beginnings. Laura learned to use the motor early and underwent several iterations to build her contraption. She had her first build that satisfied the prompt in under 10 minutes (Figure 4.26b) and went on to experiment with a walking bot (Figure 4.26c). Rose was helped by an assistant to train her *Smart Motor*. She, too, started by attaching an arm and making it wave before brainstorming an ice cream shop idea. Figure 4.26a shows Rose's ice cream shop with a rotating platform that delivers her ice cream.



(a) Rose's ice cream shop has a delivery system. (b) Laura's first build. (c) Laura's final build.

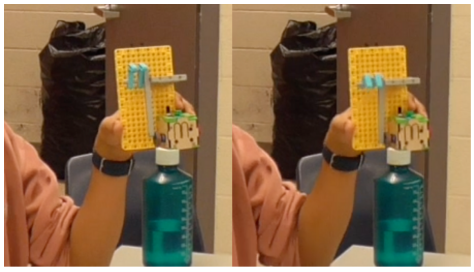
Figure 4.26: Laura and Rose's builds for activity 1 from Workshop 1.

In Workshop 2, Tim, Jason, and Keshav (pseudonyms) started by building a simple hand. Jason said he wanted to make something complex initially but didn't

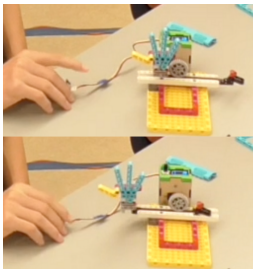
start working on it until he had something working with SM1 (Figure 4.27a). He built another waving contraption using a cam mechanism with SM2 (Figure 4.27b). Tim, who also had a simple hand-waving mechanism working, wanted to do more and built an arm on a beam that slid left and right under the SM2 motor using a rack and pinion mechanism (Figure 4.27c). Keshav started to explore beyond the simple mechanism he had initially built but ran out of time (Figure 4.27d).



(a) Jason's first build.



(b) Jason's second build.



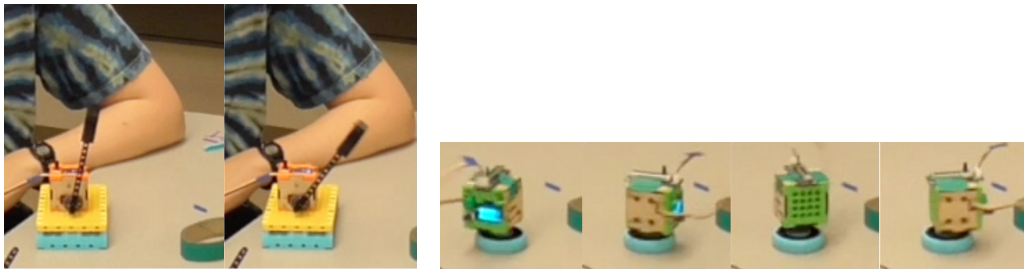
(c) Tim's waving hand.



(d) Keshav's build.

Figure 4.27: Images of projects from Group 1 from Workshop 2 for activity 1.

Like Group 1, Group 2 students started with a simple waving mechanism using the SM1, as shown in Figure 4.28a. Jeena (pseudonym) played around with the SM2 for a while but decided to give it to Liam (pseudonym). He built a rotating bot with the motor attached to a wheel and a sliding potentiometer on top and trained it to switch direction with the joystick, as shown in Figure 4.28b. The smaller number of SM2s on each desk meant not everyone could use an SM2 motor in their final design.

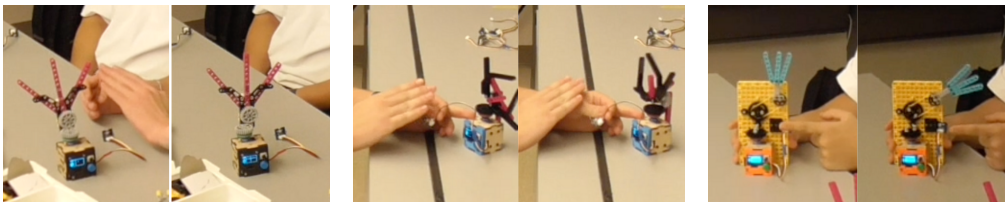


(a) Basic waving contraption the Group 2 build.

(b) Liam's rotating bot continuously spun in one direction until the potentiometer was adjusted.

Figure 4.28: Group 2's builds for activity 1 in Workshop 2.

In Group 3, they first trained their motors without the arm. Adam (pseudonym) suggested that the arm could be orthogonal to the motor. Jack (pseudonym) said they could do it with orthogonal gears. Adam and Jack worked together and had similar builds, with gears attached at 90 degrees like bevel gears (Figures 4.29a and 4.29b). Mike (pseudonym) started the build like Adam and Jack with two orthogonal gears but kept adding more and more pieces to make it "a convoluted mechanism" shown in Figure 4.29c.



(a) Adam's build.

(b) Jack's build.

(c) Mike's convoluted waving mechanism.

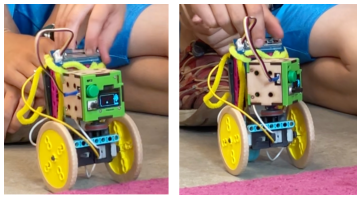
Figure 4.29: Pictures of group 3's build show the use of gears to change the plane of rotation.

Session 3: Novel Engineering with Smart Motors

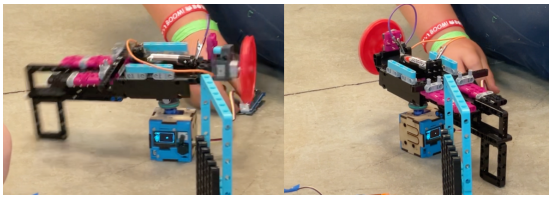
In Workshop 1, the students decided to work individually to pursue their ideas. They used DC motors, wheels, SM1 type *Smart Motors*, and LEGO® SPIKE™ Prime kit pieces to accomplish their goals. Broadly, the builds can be divided into

wall-breakers-designed to break down the walls to help bunnies reach the farm, and transporters - to transport bunnies and Mr. McGreely to another place.

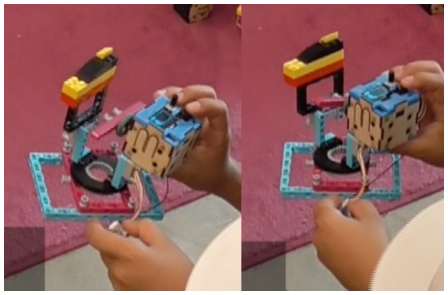
In Group 1, Ben and Dan built a wall breaker project to help bunnies tear down the wall to enter the garden. Ben built a portable "laser gun" that he trained to point at different angles with a potentiometer. Similarly, Dan built a saw on the end of an arm he trained to swing at different angles. Figures 4.30a and 4.30b show Ben and Dan's works. Similarly, Brad from Group 2 had a cannon to help the bunnies (Figure 4.30c), and Max from Group 3 built a massive hammer to knock down the walls (Figure 4.30d).



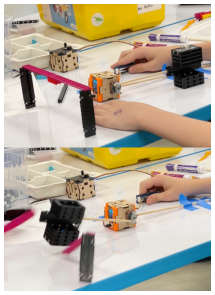
(a) Ben's portable bot can tear down walls for bunnies with a laser.



(b) Dan's saw can be oriented at different angles to cut the wall.



(c) Brad's cannon can orient at different angles to launch the cannon balls.

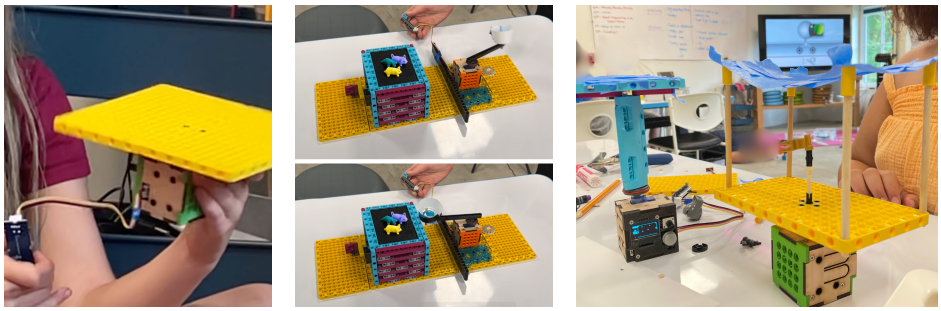


(d) Max's hammer knocks down the walls.

Figure 4.30: Collection of wall breakers from Workshop 1 for Activity 2.

Ava, Laura, and Rose built transporter-type projects. Laura and Rose's idea was to help Mr. McGreely and the bunnies. Laura's idea was to move Mr. McGreely to another place somehow so he could build another farm and let the bunnies enjoy his current farm. So, she built a rotating platform for Mr. McGreely and the bunnies.

(Figure 4.31b). Rose's idea was to have two farms with enough food for both. So she built two farms and a mechanism for the bunnies to go back and forth over the wall (Figure 4.31b). Ava built a rotating platform on *Smart Motor* to jump onto the moving trampoline so the bunnies could jump over the wall (Figure 4.31c).



(a) Lauras's rotating lift allows folks to go places.

(b) Rose's lift to help bunnies hop over the wall to the garden.

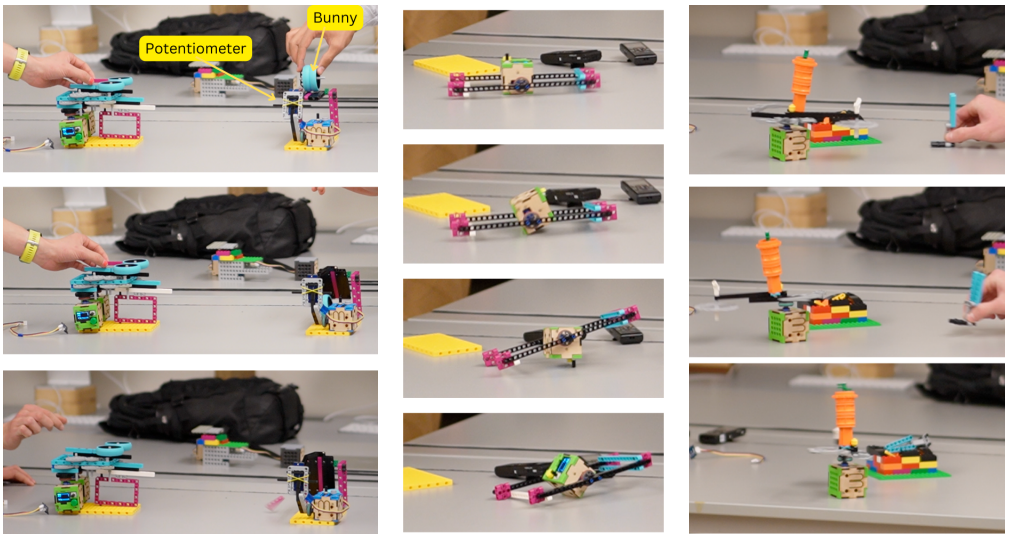
(c) Ava's trampoline and rotating platform allow bunnies to jump over the wall.

Figure 4.31: Collection of transporter-type projects from Workshop 1 for Activity 2.

In Workshop 2, they used both SM1 and SM2 type Smart Motors. Three teams used the SM2 motor. In Group 1, Tim and Keshav built a shooting mechanism with a geared-up SM2 motor to make it shoot LEGO® beams as fast as possible (Figures 4.32a). Liam used an SM2 motor to make a decoy bunny that would run around continuously to distract the farmer (Figures 4.32b). Lastly, Jeena's team used an SM2 motor to build a rotor to remove the bunnies when they got too close to the farm (Figures 4.32c). In all three cases, the students didn't train the motor; instead, they controlled the speed using the onboard potentiometer.

Liam's was the only project built for the bunnies. The rest of the projects were designed for the farmer. The projects can be classified into trap-type builds and hunting-type builds. Group 1 had both styles of build. Jason built a trap door mechanism with a potentiometer and a motor controlling the trap door. The potentiometer would trigger the trap door with a slight movement in the door

(Figures 4.32a). Then, Tim and Keshav's shooting mechanism would hunt the trap bunny.



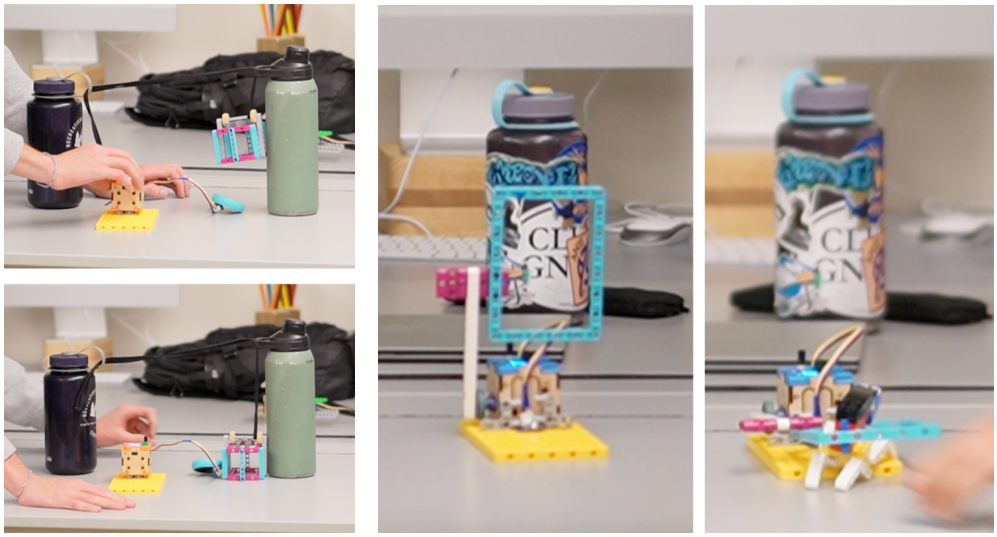
(a) Tim, Jason, and Keshav had a trap-and-hunt system.

(b) Liam's decoy bunny to distract the farmer.

(c) Jeena's team's rotating bunny remover with a bonfire nearby.

Figure 4.32: Collection of projects using the SM2 type *Smart Motors* from Workshop 2 for Activity 2.

Adam used water bottles and a string to create a pulley-like system to drop the cage when the bunny got close to the sensor (Figure 4.33a). Lastly, Mike and Jack, Figure 4.33b, had a mousetrap-like system that would trigger when the bunny stepped on the yellow LEGO® plate. Jeena's build, as explained above, would fall under the hunting type of build.



(a) Adam's trap with a pulley system.

(b) Mike and Jack's bunny trap was designed to injure them.

Figure 4.33: Collection of projects using the SM1 type *Smart Motors* from Workshop 2 for Activity 2.

4.5.3 Discussion

The workshops with V3 showed that *Smart Motors* has an easier learning curve, and the ease of use of *Smart Motors* allowed students of different age groups to apply their ideas to design solutions creatively. It showed that *Smart Motors* has the potential to be used as a tool to further creativity and innovation in engineering design workshops. I will discuss the results to answer the two questions below.

How can Smart Motors be integrated into the classrooms to support STEM education?

The results showed the impact of *Smart Motors* in engineering design workshops for a wide age range of students- from fourth grade to high school. The easy-to-get-started design and the easier learning curve of *Smart Motors* allowed students to quickly learn and implement *Smart Motors* to design creative and out-of-the-box solutions in the short amount of time they were provided. The initial

success of the prompt allowed the students to gain the confidence to take risks and challenge themselves to build complex designs. Moreover, the high success rate in the classroom created and maintained a positive atmosphere where the students felt successful while fully engaged in the design process.

Smart Motors can be an approachable, hands-on, and practical example to introduce machine learning and artificial intelligence and discuss their current uses, risks, opportunities, and ethics. In the workshops, the instructors used *Smart Motors* to demonstrate how machine learning works through data input and how the motor responds to the sensor based on user inputs. In addition, the V3 version of *Smart Motor* allows advanced students to add more sensors and reprogram them with other ML algorithms and can work as a toolkit for experimentation. So, they can be used as an entry point to discuss topics of ML and AI and practice their implementation.

Novel Engineering has been successfully implemented in literacy classrooms, especially with elementary-level students [88]. As demonstrated in the workshops, in Novel Engineering *Smart Motors* can be used as another tool in teachers' toolboxes, along with the regular build materials like cardboard, LEGO®, tape, and scissors, that can quickly be used to "animatronize" the builds. In Workshop 1, we observed the students use *Smart Motors* in various creative ways, integrating with LEGO® and other materials like DC motors and wheels. In Workshop 2, several students used SM2 *Smart Motors*, which can continuously run at a preset speed without needing a sensor or training, along with SM1. Combining *Smart Motors* with Novel Engineering can enrich the students' engineering experience by allowing them to express their ideas more creatively by animating them easily.

Finally, activities with *Smart Motors* that enhance students' skills, such as problem-solving, creativity, and collaboration, develop their engineering

capabilities. Activities focused on building with a pulley system or actuators like rack and pinion can help consolidate their knowledge about mechanisms.

What results emerged through this integration?

Solution Diversity: *Smart Motors* provides the ability to train the motors to behave the way you want and has a form factor that supports building. In both workshops, the students created projects that were unique and out of the box. With a simple prompt like "build a hand that waves" or an elaborate prompt like listening to the story and building solutions for the characters, students' various and unique builds showed how *Smart Motors* supports solution diversity.

Engagement: The students were highly engaged, as evidenced by how much time they spent on building their projects without being distracted, in both workshops' activities, spending time collaborating, perfecting their designs, and trying out something new.

Risk-taking to design with complexity: The students designed out-of-the-box solutions with various levels of complexity. Considering they were using a new tool and had limited time to design, the number of iterations and the ambitious, complex design they built could have left them without working builds at the showtime. The ease of use of *Smart Motors* and the many design opportunities it afforded allowed the students to undertake the risk of pursuing designs with complexity.

Creativity and Innovation: Students in both workshops generated ideas and builds that were unique and creative. Projects like the decoy bunny with SM2 in Activity 2 in Workshop 2, humanoid in Activity 1 in Workshop 1, and the implementation of different mechanisms to build the "Hello World" are some examples of creative and innovative projects.

Focus on the Build: In both workshops, the students spent minimal time training the *Smart Motors* and most of the time building and getting the design right. From the beginning, the students focused on building and finding the right pieces to get the first prototype working and then adding more features or building a new design. They would either figure out how to train the *Smart Motor* or get it trained at the beginning of their activity. They seemed confident in figuring out how it would fit with the build quickly and seemed to save the training/retraining for the end.

Works with different ages: Participants in the two workshops ranged from 10 to 18 years old, representing users from a wide span of cognitive development stages. The difference between the two workshops was that some younger students struggled to train their motors, and the older students were very comfortable figuring that out. The younger kids were using a different UI version with multiple steps to train, play, and save data, so they were dealing with a more complex UI. The update on the UI was made based on the observation from Workshop 1. However, despite the difficulty, both Workshop 1 and Workshop 2 students successfully implemented *Smart Motors* to design for the prompts.

4.6 Discussion

We have implemented *Smart Motors* in many more classrooms representing various backgrounds. By presenting the three studies, I explored the integration of *Smart Motors* into STEM classrooms, highlighting their potential to enhance learning and engagement across various age groups and educational contexts. For each case, I discussed to address two questions:

1. How can *Smart Motors* be integrated into classrooms to support STEM education?

2. What results emerged through this integration?

I have already pointed out the differences in versions of *Smart Motors* used in the four workshops I described above. Despite varying form factors and user interactions, the underlying principle remains the same across different versions: *Smart Motors* can be programmed without using computers and are easily integrated into a build. Throughout the workshops, students quickly grasped this concept, enabling them to concentrate their time and energy on problem-solving.

Smart Motors have been used with students ranging from second graders to high school seniors in various settings, including art, storytelling, science investigation, and engineering design. This demonstrates the versatility and adaptability of *Smart Motors* across different contexts. With good teachers, *Smart Motors* can be a practical tool for teachers to discuss machine learning concepts such as data, training, uses, and ethics with students. They can also enhance creativity, innovation, and engineering skills in projects involving materials like Popsicle sticks, cardboard, and LEGO® pieces, with great results.

Moreover, Smart Motors allows students to experiment with additional sensors and advanced machine learning algorithms in the V3 version, making them suitable for further explorations in machine learning and artificial intelligence topics. Integrating *Smart Motors* with Novel Engineering enriches the engineering experience for students, allowing them to animate their builds using materials like cardboard and LEGO®. These activities enhance problem-solving, creativity, and collaboration while developing students' engineering capabilities.

Smart Motors can be used in hands-on projects that require minimal teacher intervention, enabling teachers without prior robotics experience to focus on student learning. They can support STEM education by teaching robotics concepts

and facilitating discussions on a wide range of topics, including ML and AI, environmental science, game design, literature, and storytelling, in an interactive manner.

Below, I summarize the findings on integrating *Smart Motors* in STEM lessons.

1. *Solution Diversity*: Students showcased a wide range of diverse and unique solutions to the prompts, highlighting the flexibility and adaptability of *Smart Motors*. Projects varied from simple builds to complex and innovative designs.

2. *High Engagement*: Students were deeply engaged, as shown by the amount of time they spent on building their projects without getting distracted and discouraged, in the activities, actively collaborating, refining their designs, and exploring new ideas. The hands-on nature of the projects kept students involved and motivated throughout.

3. *Creativity and Innovation*: Students generated creative and innovative solutions to engineering problems using *Smart Motors*.

4. *Risk-Taking and Complex Designs*: The user-friendly and versatile nature of *Smart Motors* inspired students to take risks and pursue complex designs. The low risk of failure allowed students to iterate and confidently enhance their projects.

5. *Enhanced Collaboration and Communication*: With the help of good teachers running the workshops, the group projects fostered effective teamwork and communication. Students collaborated well, shared ideas, and supported each other in understanding and utilizing the technology.

6. *Self-Directed and Independent Learning*: Students independently explored

and experimented with *Smart Motors*, pushing the boundaries of their initial designs and developing self-directed learning skills.

7. *Rich Discussions and Critical Thinking*: Throughout the workshops, students engaged in enriching discussions about their observations, design choices, and the underlying concepts. This encouraged critical thinking and deeper understanding.

8. *Application of Interdisciplinary Knowledge*: Students applied knowledge from various disciplines, including math, science, engineering, and art, to their projects. This interdisciplinary approach enriched their learning experience.

9. *Adaptability to Different Age Groups*: *Smart Motors* were successfully utilized by students ranging from second graders to high school students. Younger students required more guidance, while older students demonstrated higher levels of independence and complexity in their designs.

10. *Meaningful and Contextually Relevant Projects*: Students created personally meaningful and contextually relevant projects, demonstrating their understanding of the subject matter and their ability to apply it in practical ways.

4.7 Conclusion

Teachers can use *Smart Motors* in their classrooms and activities to promote student engagement, creativity, and learning across different age groups and educational settings.*Smart Motor* projects' self-directed, hands-on, and interdisciplinary nature promoted critical thinking, problem-solving, and innovation, making it a valuable tool for STEM education. By leveraging the ease of use, versatility, and adaptability

of *Smart Motors*, educators can create dynamic and enriching learning experiences that bridge theory and practice, foster collaboration, and inspire creativity.

Chapter 5

Usability Tests

5.1 Introduction

In Chapter 3, I described the conception, evolution, and challenges of developing a $30 trainable robotics kit for low-resource classrooms called *Smart Motors*. In Chapter 4, I discussed how we tested the prototypes in several classrooms in different contexts to understand how the teachers can incorporate *Smart Motors* in their lessons and how students engage with them. For the final version of *Smart Motors* (V3), I was interested in learning the path the users take to learn how to train and use the *Smart Motors* and the failures they encounter in that process. I wanted to study the users' mental models while engaging with a trainable robotics kit and how it evolves when they develop their understanding. I wanted to learn about the product's usability from a Human Factors perspective. For this, I designed and ran a usability test with twenty-two 7 to 15-year-old participants and asked them to interact with *Smart Motors* in various activities.

In this chapter, I outline the usability tests I conducted to assess the usability of *Smart Motors* V3. I start the chapter by explaining the purpose of the usability test,

the setup, and the method I employed. I then detail the activities and their respective outcomes. I also provide a profile of the test participants, discuss the results, and conclude the chapter with a summary.

5.2 Background and Purpose

Usability is an important aspect of a human-computer interaction (HCI) system. Brian Shackel, the pioneer of usability in HCI, defined the usability of a system as "the capability in human functional terms to be used easily and effectively by the specified range of users, given specified training and user support, to fulfill the specified range of tasks, within the specified range of environmental scenarios" [92]. The definition was formalized by ISO as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [93]. Using the definitions of usability, we set up a test with participants of a targeted age group where they performed tasks representative of the intended use, where we measured the times they took to accomplish a task and the number of errors they made in studying the usability of *Smart Motors*.

We successfully achieved the goal of creating a trainable robotics kit within our cost constraint and its resulting technical limitations. *Smart Motors* are designed for use and tested in a classroom or a workshop environment, where users can learn how to operate them through demonstrations and collaborative activities with other students. However, a formalized one-on-one study involving novice *Smart Motors* users can provide detailed first-hand experiences that may be challenging to obtain in a classroom or group setting. This valuable information can then enhance the product's functionality further. In addition, this will help us identify the pain points in the product and determine the kinds of support users of different age groups or

experience levels would need to be successful.

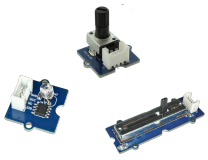
5.3 Methodology

The usability test was conducted at Tufts University's Center for Engineering Education and Outreach in February and March 2024. Guardians near Medford, MA, interested in involving their children in robotics activity, were contacted via email with a link to a scheduling app, where they could book any day of the week from 9 AM to 5 PM. Once they signed up on the app, they were sent an email with a permission form and activity details. The participants and their guardians were briefed on the test day before beginning the test. In addition to the *Smart Motors*, the following items were used for the participants to interact with during the test:

1. a LEGO® arm (Figure 5.1a).
2. sensors (light, rotary potentiometer, sliding potentiometer) (Figure 5.1b).
3. assortment of LEGO® pieces from LEGO® SPIKE™ Prime kit and LEGO® EV3 kit (Figure 5.1c).



(a) Pre-assembled LEGO® arm for the activities.



(b) Sensors used for the test.



(c) Assortment of LEGO® pieces used for the test.

Figure 5.1: Items, in addition to *Smart Motors* V3, used in the usability test.

5.3.1 Data Collection

A usability room was set up for data collection. Two cameras—one from the front and one from behind—collected video and audio data. Sketches and answers from the activity sheet were also collected as data. Sometimes, the participants preferred to give oral descriptions instead of writing their answers, which were later transcribed. The participants' ages and experiences with LEGO®, programming, and robots were collected before the test. Similarly, participants' ratings for likeability, willingness to use it again, and recommend it to their friends were collected in the post-test survey.

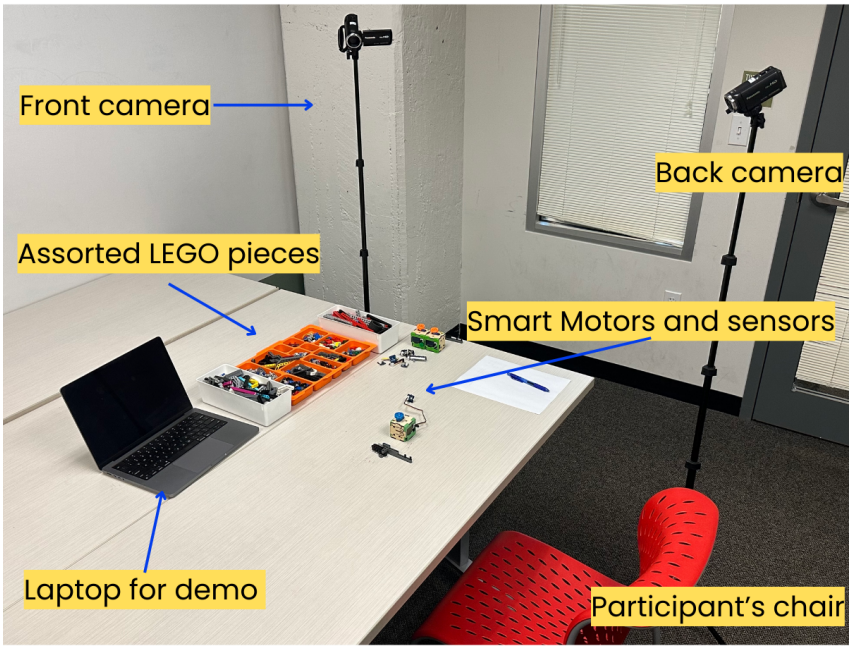


Figure 5.2: The usability test room setup at Tufts CEEO to run *Smart Motors* usability test.

5.3.2 Activities

The test was designed for 40 minutes of activities, as shown in Figure 5.3. The test started with a pre-test questionnaire (Table C.1), followed by the participants watching a minute-long training or introduction video. Once they were ready to start the activities, they were handed an activity sheet with prompts and provided materials needed to complete the task outlined in the prompt. There were four activities where they engaged with *Smart Motors* and LEGO® pieces. Each activity was allocated a certain amount of time to complete. If their guardians agreed, the participants could take extra time to complete the task. The last activity was to fill out a post-test questionnaire (Table C.2).

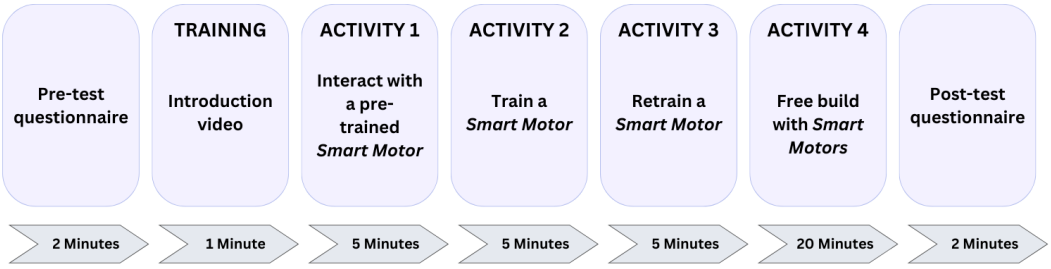


Figure 5.3: The breakdown of tasks in *Smart Motors* usability test.

Introduction video

Figure 5.4 shows screenshots of how the information was presented with captions in the introduction video to *Smart Motors*. The video had information about the following:

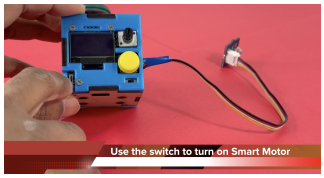
1. The position and purpose of the power switch.
2. The position and purpose of *nav* buttons.

3. The position and purpose of *selection* button and different modes.

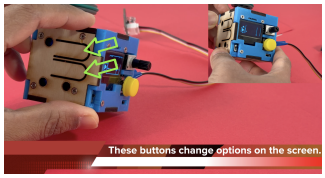
4. The light sensor.

5. The position and purpose of the potentiometer.

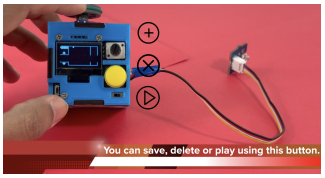
While it was not explicitly mentioned or captioned in the video, it also included a 10-second demonstration of *Playing* on *Smart Motor*, which included pressing the *selection* button with *Play* mode icon on the screen, the screen inverting the color and motor moving with the change in the light sensor. Participants were reminded to rewatch the video as many times as they wished.



(a) showing the power switch to turn on the *Smart Motor*.



(b) showing the position and use of *nav* buttons.



(c) showing *Smart Motor*'s different modes and the actions users can take using *selection* button.

Figure 5.4: Screenshots from the introduction video from the usability test.

Activity 1

The first activity involved interacting with a pre-trained smart motor with a light sensor. The *Smart Motor* stored two training data points (Figure 5.5) that would move the motor one way when the light sensor was covered and the other way when the light sensor read the ambient light reading.

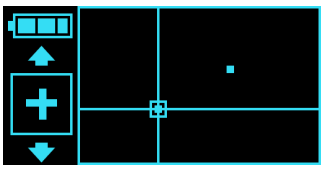


Figure 5.5: The screen of a pre-trained Smart Motor with two data points.

The participants were asked to do the following:

1. Connect the LEGO® arm to the *Smart Motor*
2. Observe what happens when you cover and uncover the light sensor with your hand.

In this activity, I asked the participants to describe the behavior of the pre-trained motor (Table C.3). I had them investigate whether the buttons and icons allow self-discovery in *play* mode. I wanted to investigate how the participants used the information on the screen to make sense of the motor behavior. I measured how long it took the participants to discover the play mode and what was happening. With the data from the test, I wanted to find out what kinds of interventions are required for participants of different ages to guide them to play mode.

Activity 2

Activity 2 involved training a *Smart Motor*. The participants were given a *Smart Motor* and a LEGO® arm. Their task was to figure out how to make the LEGO® arm wave with the sensor. We call this the Hello World activity. They could use a sliding potentiometer instead of the light sensor for ease of use. After the interaction, the participants were asked to share their thoughts on why the motor behaved the way it did and rate and share the task's difficulty level. I wanted to discover how this activity changed the participants' mental models. I also measured how long each participant took to determine how the Smart Motor worked and the kinds of data they took. The prompts and questions on the activity sheet are in Table C.4.

Activity 3

The third activity was to alter the behavior of the *Smart Motor*. I asked them what they would change before attempting to retrain the motor. With this activity, I wanted to confirm whether the participants could make the motor behave how they wanted. The prompts and questions for activity 3 are in Table C.5.

Activity 4

Activity 4 consisted of three parts (Table C.6). In the first part, I asked the participants to brainstorm an activity they had recently done. Then, they were asked how they could represent the activity with *Smart Motors* and LEGO® pieces. In the second part, they were asked to build the representation of the activity using the available materials in 15 minutes. Finally, in the last part, they were asked to share what they built and answer some questions. With this open-ended activity, I wanted to investigate how users can use *Smart Motors* to bring their imagination into reality and what kinds of projects they create. I also want to study the characteristics of play and their states.

Below is a summary of the prompts for the four activities.

1. Activity 1 - Connect the LEGO arm and observe what happens when you cover and uncover the sensor with your hand.
2. Activity 2 - Use the Smart Motor and teach it to do a waving motion.
3. Activity 3 - Use the same motor and make the motor wave differently.
4. Activity 4 - Think of an activity you did this summer. Use Smart Motors and LEGO® pieces to represent the activity.

5.3.3 Data Analysis

The information about the participants, including their age, experience of using robots, LEGO®, and programming, and comfort level for the test from the pretest questionnaire, were used to investigate their correlation with the metrics calculated from the participants' engagement with *Smart Motors* and their responses. The post-test data evaluated the robotics kit's likeability and usefulness. The answers to the third question of the post-test survey were operationalized as the participant's assessment of the product for the children of their age group.

The following metrics were calculated from the activities:

Discoverability as a feature of Smart Motors

The participants' paths to discovering features were evaluated and compared to the idealized path described below. The mistakes, either caused by faulty *Smart Motors* or user error, were noted. The participants were allowed to ask questions, and the answers may have led them to complete the task. In such cases, the questions and answers were noted. Discoverability of the *play* mode as a feature and Trainability of *Smart Motors* as a feature were used to describe the path to the discovery of features.

- Discoverability of the *play* mode as a feature

  The time of discovery of *play* mode or ToP in seconds is how long it took the participants to activate the *play* mode from when the *Smart Motor* was turned on in activity 1. In an idealized scenario, a participant would follow the following steps to activate the *play* mode on a pre-trained *Smart Motor*.

  1. Turn the *Smart Motor* on.

2. Notice that the *play* icon is displayed in the left panel of options.

3. Press the *selection* button to activate the play mode.

Since this is the first time the participants have used Smart Motors, they might press the *nav* button to explore other options or turn the potentiometer to see the motor move.

- Trainability of *Smart Motors* as a feature

  The time of discovery of *training* or ToT in seconds is how long it took the participants to *train* the *Smart Motor* and activate the *play* mode in activity 2. In an idealized scenario, a participant would follow the following steps to *train* the *Smart Motor* and activate the *play* mode:

  1. Turn the *Smart Motor* on.

  2. Notice that the add (+) icon is displayed in the left panel of options.

  3. Set the sensor to read a certain value and move the motor to a position.

  4. Press the *selection* button to add a data point.

  5. Repeat for one or more points for different motor positions and sensor readings pairs.

  6. Use the *nav* buttons to find the play icon in the left panel of options and press the *selection* button

  Activity 3 was used for redundancy to confirm the trainability of *Smart Motors*. The self-assessment of correctness of retraining was used to evaluate the participants' rating of their ability to retrain the motor. The ratings for challenges were compared for activities 2 and 3, reasons were investigated,

and themes were extracted to identify the pain points for *training*.

Mental Models

The mental models of *Smart Motor* were investigated using the descriptions of motor behavior from the video and activity sheet data from activities 1 and 2. The change in the description indicated the evolution of the mental model. Some variations of how the motor's movement depended on the light sensor's amount of light received were expected from the participants in their descriptions in Activity 1. Similarly, some variations of how the user saved the motor and light sensor pairing by adding data points and how the motor used this data in *play* mode were expected from the participants in their descriptions in Activity 2. The sense-making of data and motor behavior using the screen (dots and lines representing the motor position and sensor reading) was also analyzed.

Usability of Smart Motors

The usability of *Smart Motor* was evaluated using the projects the participants built during Activity 4 and their successful completion. I looked for the solution diversity by looking at the number of *Smart Motors* used, types of sensors used, and nature of projects built. I also looked at the participants' ratings of how well they could replicate their ideas into reality using the *Smart Motors*. Other metrics like likeability, intention to use again, and recommendation to their friends from the post-test survey were also analyzed.

5.4 Results

Twenty-two participants, aged 7 to 15, participated in the usability test. Table D.1 shows the responses from the participants, and Table D.2 summarizes the responses

from the pre-test survey. 17 out of 22 said they had played with robots before, and 18 out of 22 had done some programming, of which 11 had Scratch, 1 had Python and Java, and 1 had Scratch and Python experience. Everyone said they had played with LEGO® before, and all but 1 said they liked playing with robots. 15 said robots are fun and cool, two said they like to make and see them do amazing things, one said for the bragging rights, and 1 participant said they don't get enough time to play with it as the reason they like playing with robots. 7 out of the 17 participants who had played with robots had played with LEGO® robotics: 4 with LEGO® SPIKE™ Prime and 3 with LEGO® Mindstorms.

In the section below, I will present the results of the usability study.

5.4.1 Path to the discovery of features

In this section, I will present the data to show how the participants discovered the features of *Smart Motors*. *Discoverability of the play mode as a feature* and *Trainability of Smart Motors as a feature* will be used to describe the *Path to the discovery of features*.

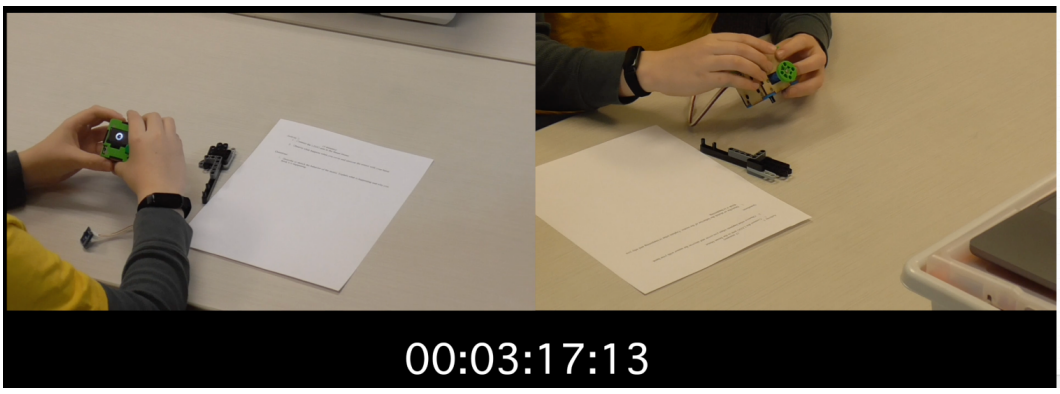


Figure 5.6: Screenshot of video data showing participant 15 exploring *Smart Motor* during Activity 1

Discoverability of the play mode as a feature

From the first activity, we measured the time participants needed to figure out the *play* mode on their own. This was measured from when they turned on the motor to when they enabled the *play* mode. Figure 5.7 shows the participants' different paths, from turning the motor on to enabling the *play* mode. The ideal path is Path C, where the participant turns on the motor and presses the *selection* button. Path F is for participants, where I intervened and showed them how to enter *play* mode, which is ignored from the data.

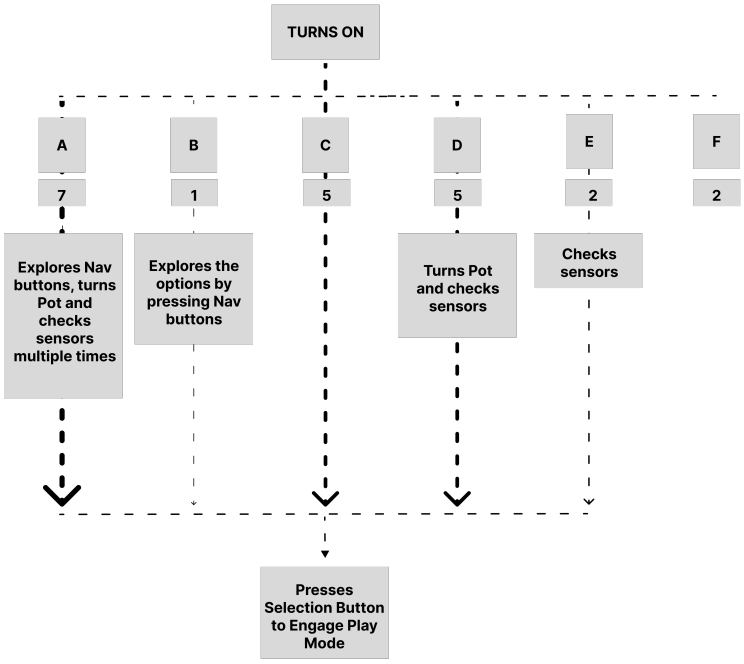


Figure 5.7: Picture showing possible routes taken by participants to discover *play* feature.

Table 5.1 shows the participants' age, time of discovery of *play* mode or ToPs, and their paths. The average ToP was 33 seconds, with a standard deviation of 32.57. Figure 5.8 shows the results in a chart. The overall time participants took to enter *play* mode was short, and the younger participants had smaller ToP values than the older participants. From the chart, it is clear that younger participants used

path C more than other participants, which resulted in a smaller ToP value. No clear patterns emerged from the scatter plot, except that participants who took path A spent the most time in Activity 1.

Table 5.1: The time of discovery of *play* mode or ToP
and path taken by the participant as shown in Figure 5.7

SN	Age	ToP (in seconds)	Path
6	7	5	E
7	7	11	D
22	7	6	C
3	8	5	C
5	8	5	C
16	8	56	A
19	8	NA	F
2	9	19	D
8	9	4	C
11	9	59	A
14	10	81	A
18	10	26	B
4	11	33	A
1	12	20	D
9	12	39	E
15	12	19	D
21	13	64	A
12	13	NA	F
10	14	5	C
13	14	16	D
17	14	127	A
20	15	60	A
Average ToP		33	
Standard Deviation of ToP		32.57	

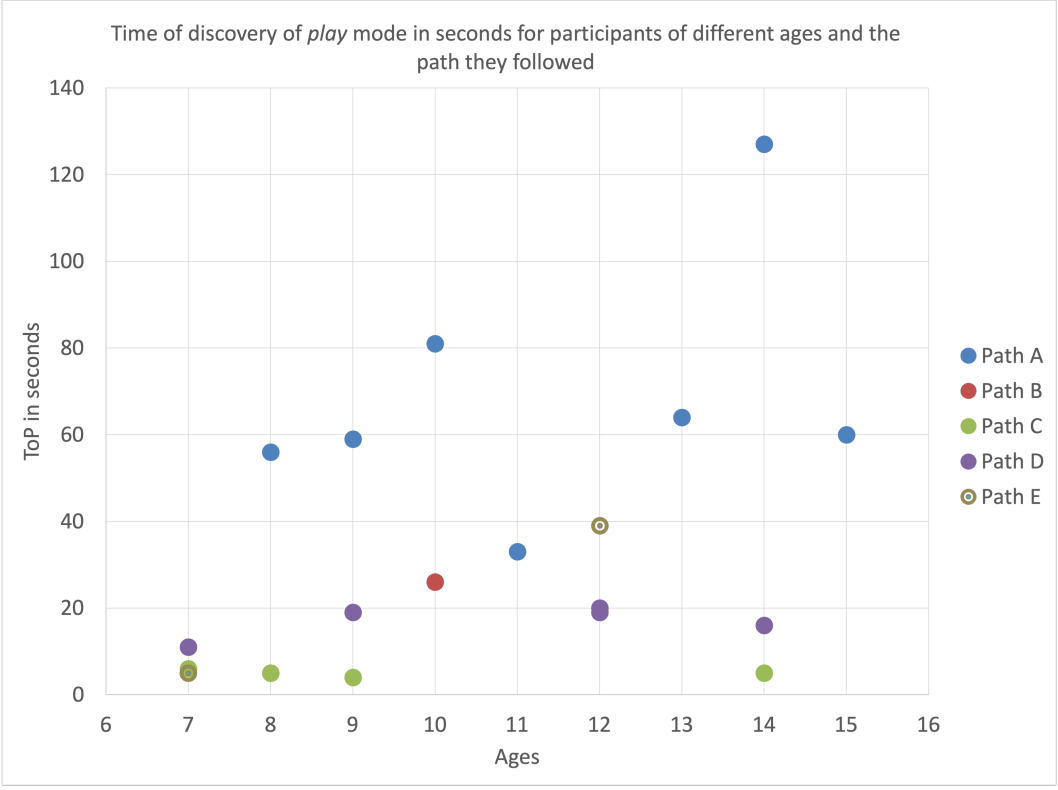


Figure 5.8: Scatter plot showing the time of discovery of *play* mode for participants of different ages and the path they followed.

Based on the results in Table 5.1 and summarized in Table 5.3, the 7-9-year-old age group could discover the *play* mode in the shortest time, under 19 seconds. Age group 13-15 took about a minute to enable the *play* mode. Table 5.2 shows the frequency of paths the participants took to discover the *play* mode. Most participants explored the navigation buttons, potentiometer, and sensors before engaging in the *play* mode. 5 participants engaged in *play* mode right away, 4 of which were from the 7-9 age group.

Table 5.2: Frequency of participants' path to discovery of *play* mode

Path	Total occurrence
A	7
B	1
C	5
D	5
E	2
F	2

Table 5.3: Average and Standard Deviation of ToP across three age groups

Age group	Average ToP in seconds	Standard deviation of ToP
7-9	19	22
10-12	36	23
13-15	54	48

Trainability of Smart Motors as a feature

Table 5.4 shows the time of discovery of *training* or ToT, which is the time it took the participants to take data on a *Smart Motor* to *train* and *play*. The table also shows if they needed any assistance that was critical to the process. Asking for assistance, such as requests to reiterate the prompt, replay the introduction video, and say what the buttons might do, was not considered critical to be included in the table. Participants were offered assistance when they took a long time to make progress to ensure they had enough information to go to the next step. Ultimately, everyone had at least two data points on *Smart Motors*, and the motor moved to two distinct positions for distinct sensor values.

Table 5.4: Participants and their age with the time of discovery of *training* (ToT), time to retrain, whether they were assisted in Activity 2, and their self-assessment of ability to retrain in Activity 3.

SN	Age	ToT (secs)	T to retrain (secs)	Assisted?	Self-Assessed ability to retrain
6	7	477	390	Yes	Not exactly
7	7	576	97	Yes	Yes
22	7	496	148	Yes	Yes
3	8	310	73	Yes	Not exactly
5	8	655	35	Yes	Yes
16	8	471	39	Yes	Yes
19	8	479	400	Yes	Not exactly
2	9	370	196	No	Yes
8	9	402	167	Yes	Not exactly
11	9	313	454	Yes	Yes
14	10	84	352	No	Not exactly
18	10	265	206	No	Not exactly
4	11	210	38	No	Yes
1	12	261	63	No	Yes
9	12	564	364	No	Not exactly
15	12	283	81	No	Yes
12	13	47	125	No	Yes
21	13	137	213	No	Yes
10	14	261	45	No	Yes
13	14	210	36	No	Yes
17	14	95	129	No	Yes
20	15	162	185	No	Yes
Mean		324	174		
Std. Dev.		173	135		

Figure 5.9 shows the scatter plot of ToT for different ages and if they required

any help. There is a distinct cluster of participants from age group 7-9 who needed help and took the most time to train their *Smart Motors*.

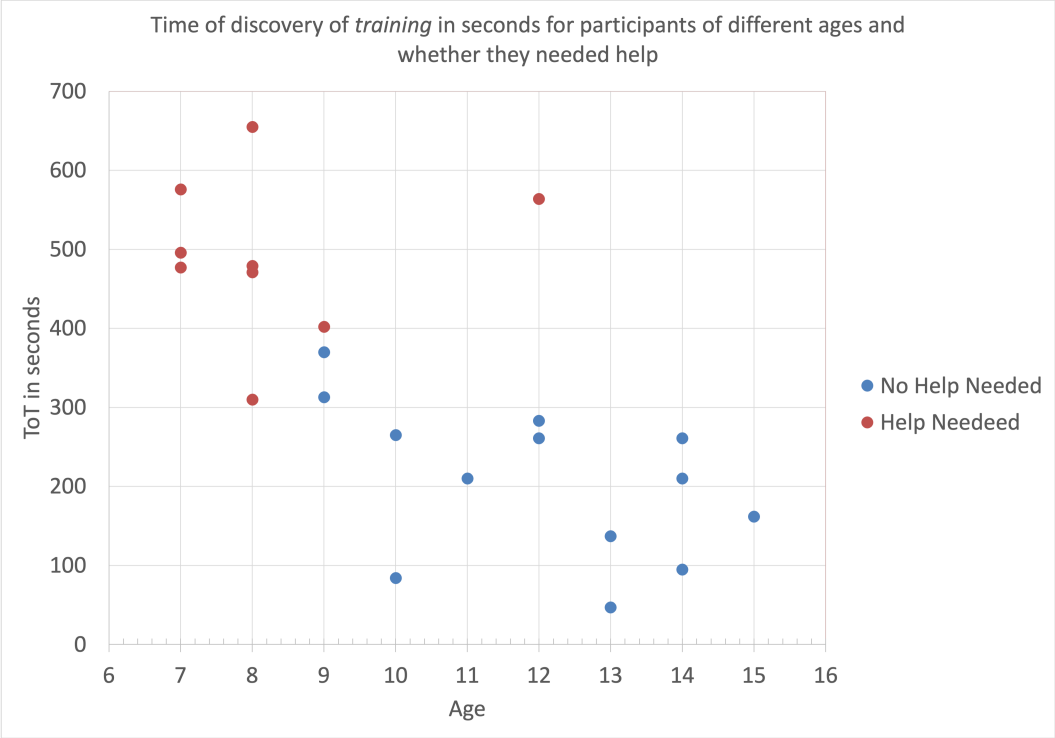


Figure 5.9: Scatter plot showing the time of discovery of *training* for participants of different ages and whether they needed assistance.

Here is a sample of questions asked to the participants to assist them:

1. What do you think the icons on the screen mean?
2. Why do you think the lines are moving to the left and right?
3. What do you think the dots on the screen mean?
4. Do you know there are buttons on the side that will change the mode?
5. Would you like to see how the dots were arranged in the previous *Smart Motor*?

Two participants used the idealized path, and two were close to following it to

train their *Smart Motor*. Most participants experimented with the potentiometer and sensor, adding dots, removing them, and finally figuring out how to make the LEGO® arm move with the sensor.

Table 5.4 also shows the time participants used to retrain their *Smart Motors*. They were asked if they could make the motor behave the way they wanted, and their answers were used to assess their ability to retrain the motor. The average time to retrain the *Smart Motor* was 174 seconds, almost half as compared to the time it took them to discover the training.

Figure 5.10 shows the scatter plot of time participants of different ages took to retrain their motor and their self-assessment of their ability to retrain the motor in different colors. Younger participants who took fewer seconds to retrain the motor said they could not make the motor behave exactly as they wanted. Older participants said they could retrain the motor to behave as they wanted. Comparing the two plots in Figures 5.9 and 5.10, we can see the younger participants' time to retrain reduced compared to the time to train. Some participants took longer to retrain as they wanted the behavior to be more complicated and spent much time removing and adding many dots. Overall, the two charts show that older participants, notably those 13 and above, spent fewer seconds training and retraining the *Smart Motors* without help and felt successful compared to the younger participants.

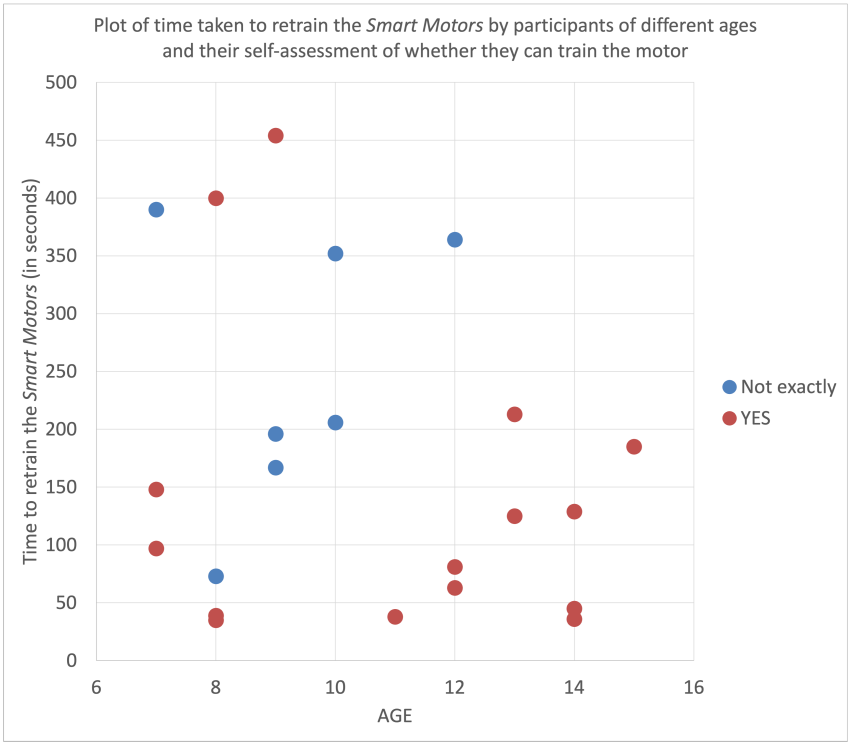


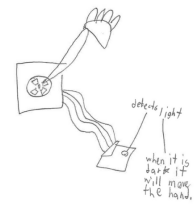
Figure 5.10: Scatter plot showing the time taken to retrain the *Smart Motor* by participants of different ages and their self-assessment of whether they could retrain properly.

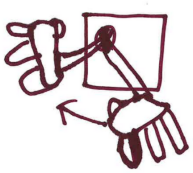
5.4.2 Mental Models

Participants' mental models on how the *Smart Motors* worked and how they got the motors to work were evaluated by asking them to sketch, answer, or verbally express how they thought the *Smart Motors* worked after each activity. The evolution of participants' mental models was tracked through the activities.

After the first activity, when the participants enabled the *play* mode, they discovered that the motor moved when they covered and uncovered the sensor. Some students preferred sketching their observations, as shown in Figures 5.11a, and some wrote using text, as shown in Figure 5.11b. The levels of detail in their answers varied; while some noted the motor behavior, others chose to talk about the relationship between dots, sensors, and motor positions. From Activity 1, it was

clear that participants of all ages could understand the relationship between a motor and a sensor in a pre-trained *Smart Motor* with two data points.





(a) Some students sketched their observations.

A It sends a signal to the moter to move.

B The motor is moving the hand in a waving motion. When I touch the sensor it tells the motor to move.

C When I cover the sensor the arm moves from dot to dot. I think the dots represent points that the motor can move to and it is reading different ones when the sensor is covered or uncovered.

(b) Some used words to write their observations.

Figure 5.11: Sample of participants' responses on what they observed with the pre-trained *Smart Motor* on Activity 1 (from Table D.3 and Figure D.1)

From the responses in Table D.3 and Figure D.1, we learn that participants of all ages (7 to 15) were able to characterize the relationship between motor and sensors correctly at different levels of detail. As expected, their responses were variations of how the motor's movement depended on the light sensor's amount of light received.

Most participants were given a sliding potentiometer instead of a light sensor for the second activity for ease of use. After the second activity, after training the *Smart Motor*, the participants sketched, wrote, or verbally described their thinking on why the motor was behaving the way it was behaving (Table D.4 and Figure D.2). Most participants connected the relation of the dots they put on the screen with the motor positions and sensor values. The motor followed the dots or points they had recorded on the screen. One participant, Participant 13 (age 14), said, "*I think the motor behaves this way due to it snapping to the nearest position that the vertical touches*." Some of their descriptions and sketches used *time* for the sensor reading

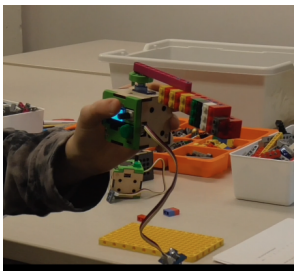
instead of the sensors' *position*, which could be construed as a misconception. However, this didn't impact their ability to train the motor accurately for different sensor positions.

There were some misconceptions about how the motor worked. One participant thought the sensor was working as a switch. Participant 8 had two motor positions for almost the same sensor value at one end of the screen, towards the left. Because of the noise in sensor readings, the sensor might read different values even in the same condition, causing the motor to move from one position to another if the motor is trained for different positions for similar sensor values. The participant correctly observed that the motor didn't move when the sensor reading was at the right extreme. However, the arm waved continuously when the sensor reading was at the left extreme, causing him to believe that the sensor was acting as a switch - the right extreme was OFF, and the left extreme was ON position. In retraining the motor, the participant wanted to switch his sensor's ON and OFF positions and make the waving occur at the other end of the sensor reading but couldn't achieve the results. Another participant mistakenly assumed that the motor was "seeing" him wave with his hand and replicating the behavior. His mental model of *Smart Motor* was that it could see and record the hand movements from the user at certain sensor values and play it back when the sensor was placed at that value.

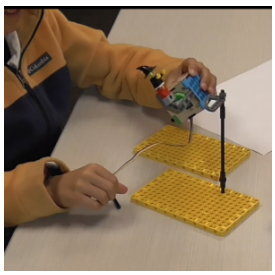
Overall, the participants connected the dots' relationship with the motor's position and sensor value and the motor's movement with the dots or points they created. In retraining the motor, they could add or delete points and change the direction of the points to change the motor's behavior.

5.4.3 Usability of *Smart Motors*

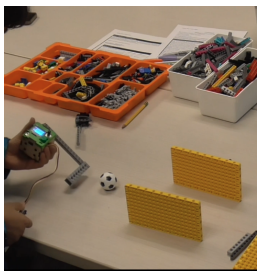
The participants had 4 minutes to think of an activity they wanted to represent with *Smart Motors*. While the prompt specifically mentions summer activities, I adapted it to include their current activities because the test was conducted in the winter. They had 15 minutes to build their projects, but some participants requested more time, and some completed early. In the end, they gave a short description and demonstrated their project. Figure 5.12 shows some projects participants built during Activity 4 (More pictures in Figures D.4 and D.5). Table D.6 shows their project description, ratings, and the improvements they want to make on their build.



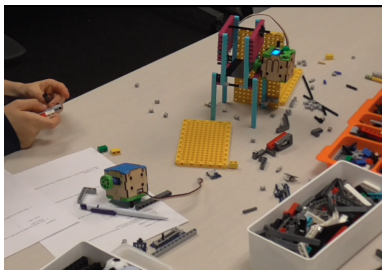
(a) Participant 5



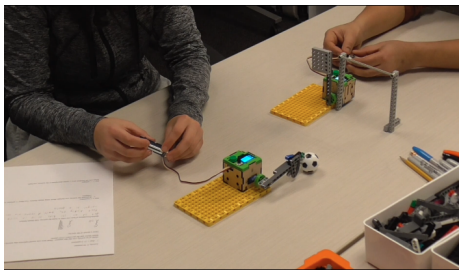
(b) Participant 6



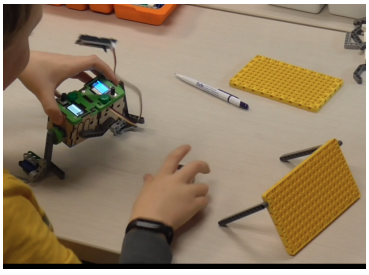
(c) Participant 7



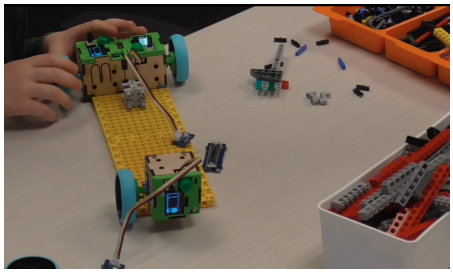
(d) Participant 11



(e) Participant 12



(f) Participant 15



(g) Participant 16

Figure 5.12: Sample of participants working on their projects during Activity 4.

Completion rate

All the participants in the usability test completed Activity 4. The fastest build time was by Participant 13, which took about six minutes, and the longest was about half an hour by Participant 21. Since the participant had completed the earlier activities in under 19 minutes and asked for more time, I allowed him to tinker for double the stipulated time. The average build time was about 17 minutes, with a standard deviation of about 6 minutes.

Ratings

The participants were asked to rate how well they could represent the activity from 1 (Very well) to 5 (Very poorly). Table 5.5 shows the summary of the ratings. Two participants rated 3.5 and 2.5, rounded to 4 and 3 for the frequency table.

Table 5.5: Frequency table of participants rating of how well they were able to represent their activity with *Smart Motors* in Activity 4.

Rating	Frequency
5 (Poorly)	0
4	1
3	6
2	7
1 (Very well)	8
Total	22

Solution Diversity

The participants had 4 minutes to develop an idea and 15 more minutes to execute it with LEGO® pieces and *Smart Motors*. Participants came up with 22 personally

meaningful ideas during a relatively short time. The diverse nature of solutions among these ideas shows that *Smart Motors* can be implemented to represent a wide range of ideas. Here is the list of the projects built by the Participants (refer to Table D.6 for detailed description and Figures D.4 and D.5 for images).

1. A scissor gripper mechanism
2. An obstacle course representing parkour activity
3. Representation of throwing and dodging a snowball
4. A swimming simulator
5. A salsa maker
6. Representation of dunking a basketball
7. Kicking football into the goal post.
8. A hockey-like game to score a goal
9. A driving car
10. Representation of a croquet game
11. A claw machine's trap door to dispense LEGO®
12. A two-player football game
13. A representation of sailing
14. An art bot to create abstract art
15. A two-legged footballer
16. A scooter
17. Representation of a flying plane to vacation.

18. Representation of a swimming activity

19. A picker arm to help build with LEGO®

20. Representation of a fencing game

21. A gripper with two controllable arms

22. Representation of cutting a birthday cake

Likeability

The participants were asked to rate if they liked *Smart Motors*, whether they would use it again, and whether they would tell their friends about *Smart Motors* (Table C.2). They could rate on a scale from 1 to 10. A rating of 10 meant Yes, and one meant No. Their responses are documented in Table D.7 and summarized in Figure 5.13.

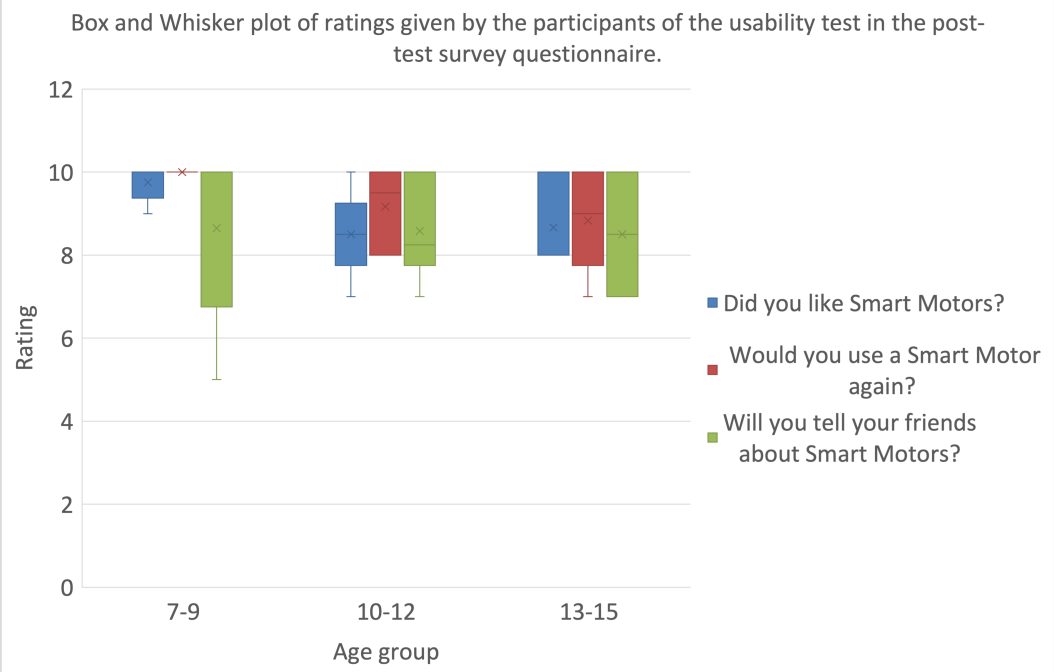
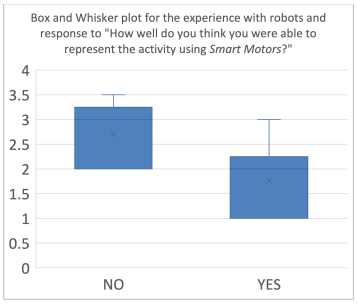


Figure 5.13: A box and whisker plot showing the usability test participants' ratings for the three post-test questionnaire questions.

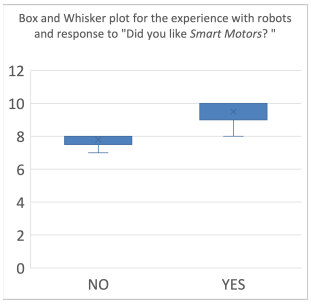
The overall ratings for all three questions were positive for the *Smart Motors*. The breakdown of ratings by age group shows that participants aged 7-9 had the highest ratings for all three questions. The single participant who rated five on the third question explained that his friends were not interested in robotics. Therefore, he didn't think they would be interested in *Smart Motors*.

5.5 Discussion

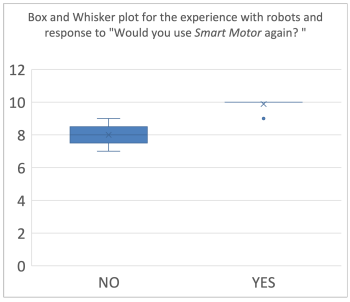
The usability test participants may not represent our target population for *Smart Motors* in terms of prior experience. More than 75% of the participants reported having some prior robotics and programming experience, and 100% reported having played with LEGO®. Figure 5.14 shows the box and whisker plots for participants with and without prior robotics experience and their ratings for different questions. The sample size for the participants without prior robotics experience was small compared to the ones with prior experience. More studies need to be conducted to study the relationship in more detail.



(a) Ratings for "How well do you think you were able to represent the activity using *Smart Motors*?" in Activity 4.



(b) Ratings for "Did you like *Smart Motors*?"



(c) Ratings for "Would you use *Smart Motor* again?"

Figure 5.14: Box and Whisker plots of the participants' ratings with and without prior experiences with robots.

In terms of discoverability as a feature of *Smart Motors*, it was clear that

Table 5.6: Average time to *train Smart Motor* for participants who took different paths in Activity 1

Path Taken	Average Time of Training (in seconds)
Path A	197.43
Path B	265.00
Path C	424.80
Path D	340.00
Path E	520.50
Path F	308.00
Average	342.62

participants could discover the *play* feature. Most young participants followed the "ideal" path to enter the *play* mode. When the *Smart Motor* has pre-trained data, it starts with the *play* option on the screen, and all the user has to do is press the big selection button. So, one explanation for this behavior could be that the young participants just pressed the button without realizing what they were doing. It is also interesting to notice that the participants who spent more time exploring the features or following Path A were the ones who were able to *train* the *Smart Motor* the fastest in Activity 2. Those who took Path B were the second fastest group to *train* the motors. This could be because, in Path B, they explore the *nav* buttons. One of the observations from this study was that the participants didn't pay much attention to the introductory video information about the Navigation or *nav* buttons. Those participants who were aware of those buttons in Activity 1 were able to figure out the different options available, and this could have potentially impacted their ability to *train* the motor.

The graph in Figure 5.9 shows a clear picture of how the age of the participants and the need for critical assistance to *train* the motor are related. Figure 5.15 shows the plot of age and need for help during training (Help needed = 1, Help not needed = 0). Based on the Spearman correlation, there is a statistically significant

relationship between the age of the participants and their tendency to need help to train the *Smart Motor*, with older children less likely to need help than younger children. The transition age for this sample was about ten years old. The regression evaluation shows the r_s = -0.84. The square of Spearman correlation coefficient R^2= 0.7056. This means 70.56% of the variability in the dependent variable can be explained by the variability in the independent variable through their relationship. The result indicates that Age likely accounts for the ability of the participants to use the product, as the participants had similar prior experience with robots and LEGO®.

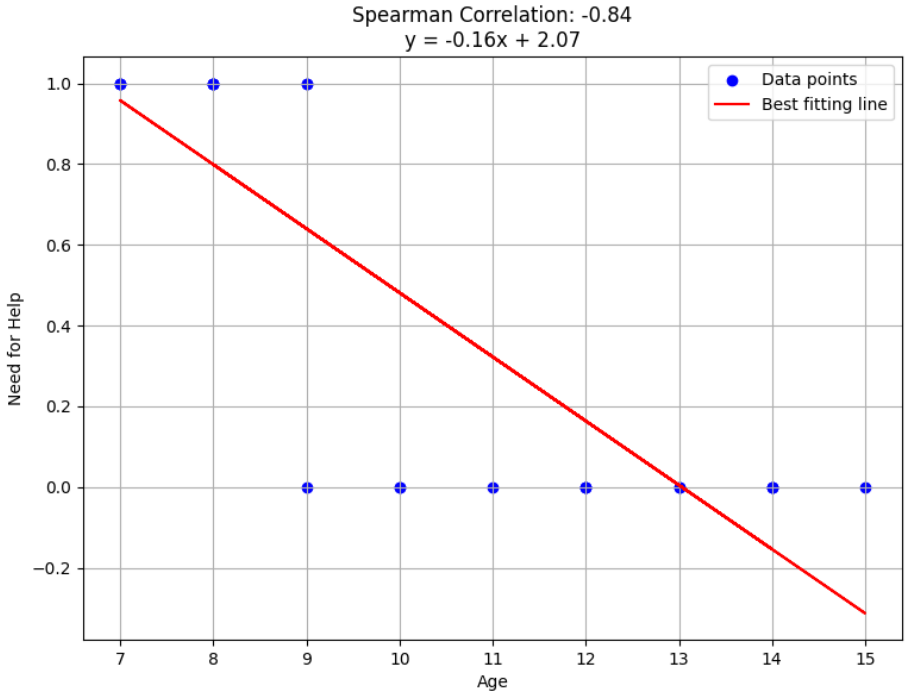


Figure 5.15: Plot showing the relationship between the age of the participants and whether they needed help to train the *Smart Motors* independently.

Table 5.7: Statistical test to find the relationship between age and the ability to train the motor in Activity 2.

Column	Test Used	Statistic	p-value	Conclusion (at = 0.05)
Age	Spearman-Correlation	-0.844603	$7.677e^{-07}$	Significant

The analysis of the participants' mental models after they enabled the *play* mode revealed that they observed the relationship between the motor and the sensor correctly. The data shown in Figure D.1 and Table D.3 and the samples chosen in Figure 5.11 show that the participants correctly established that there was a relationship between the arm moving and their blocking of light on the light sensor. Since there were only two data points, the observation was simpler. If there were more than two data points, it would have been interesting to see how the participants made sense of the motor and sensor relationship.

When the participants trained the motor, their understanding of how it worked incorporated data representation as dots or points on the screen; they could relate the dots or points on the screens to when and where the motor would move. Their understanding and explanations became more nuanced, and they talked about the motor's position compared to the motor's direction or motion. The analysis of behavior of the participants while trying to figure out the training was they relied solely on the data represented on the screen more than the position of the actual motor and sensor value.

Most of the participants, after Activity 1 (playing with pre-trained *Smart Motor*) and Activity 2 (training a *Smart Motor*), were able to explain the workings of the motor and sensor as expected. However, there were some interesting observations, as mentioned in the results. One of the participants noted that the sensor was working as a switch, which was a valid way of explaining how his motor was

behaving, but he didn't probe further to test his hypothesis. The motor's unexpected behavior resulted from training the motor to move to two distinct positions for the same environmental condition. Due to the noise in the sensor reading, the two positions had slightly different sensor values, as shown in Figure 5.16. Thus, when engaged in *play* mode and when the sensor was near the trained dataset, the sensor continued to read the noisy data, and the motor would jump between the points on its own, giving the impression of the sensor working as a switch.

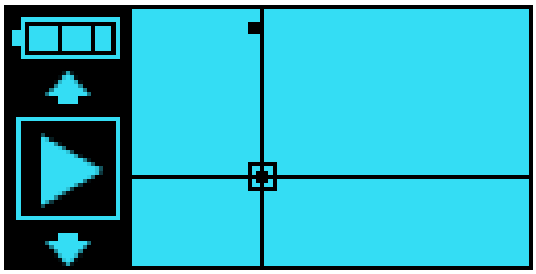


Figure 5.16: Screen showing data stored by participant 8 in Activity 2.

Another participant had a different misconception. It resulted from a feature I programmed to indicate that a data point had been stored where the motor wiggles a little when pressed the *selection* button. One of the participants somehow interpreted my suggestion that he should "show" the motor what it should do. And, by unfortunate coincidences, he stumbled upon the button and the wiggle feature right after he waved his hand in front of the motor. Thinking that the motor was "seeing" his hand, he continued to try to *train* the motor with this method. His idea of how the motor moved didn't change even after somehow he could retrain the motor to change its behavior, which impacted how well he could build his project in Activity 4.

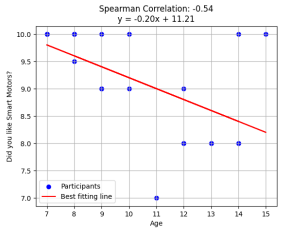
Some participants could figure out the behavior accurately immediately, and some could do so after some explorations. There were moments when the

participants went, “Oh! I get it now!” and “Ah, so this is how it works!”, which shows they figured out something that was not apparent to them initially. Most participants relied on the screen to deduce how to use the system, which shows the motor position on the Y-axis and the sensor reading on the X-axis of the XY Cartesian coordinate system. The lack of understanding of the XY Cartesian coordinate system could have impacted the ability to make the connection between the understanding of the dots’ position and motor and sensor value. However, I didn’t collect specific data to draw any conclusions.

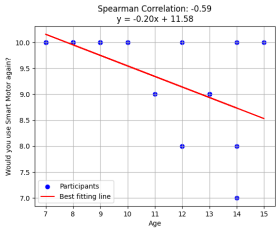
The analysis of projects built in the final activity revealed the high solution diversity. No metrics were used to measure the diversity of solutions, but observing the projects built reveals the wide range of potential projects that can be built with *Smart Motors*. The projects ranged from representing activities using moving LEGO® Minifigures attached to *Smart Motors* wheels to building interactive two-person games. There was also diversity in the number of motors and types of sensors used. 12 participants used a single *Smart Motor*, 8 used 2, 1 used 3, and the remaining one used 4 *Smart Motors*. The most popular sensor was a sliding potentiometer. Ten projects used sliding potentiometers, 8 used rotary potentiometers, and 5 used light sensors to build their projects. Overall, the possibility to use different sensors with the *Smart Motors* and attach several *Smart Motors* contribute to the possibility of using *Smart Motors* in a wide range of projects.

Finally, the post-test survey revealed that the participants rated high on all three questions. The average rating, on a scale of 1-10, where one was No and ten was Yes, for all participants for the first and third questions was above 8, and the second was above 9. Probing further by breaking down by age group, and

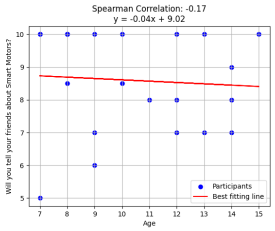
as shown in Figure 5.13, revealed younger participants in the age range 7-9 rated around 9.75 with a standard deviation of 0.42 for question 1 (Did you like *Smart Motors*?), ten on 10 for question 2 (Would you use *Smart Motor* again?), and 8.65 with a standard deviation of 1.94 for question 3 (Will you tell your friends about *Smart Motors*?). Using Spearman Correlation to investigate the relationship between participants' age and their ratings for the three questions revealed (Table 5.8) that there is a significant moderate negative correlation between the age of the participants and their responses for "Did you like *Smart Motors*" and "Would you use *Smart Motor* again?" questions. The test didn't reveal any significant correlation for the third question about telling their friends about *Smart Motors*. The simple and approachable design of the *Smart Motor* could have resulted in younger participants rating higher than the older participants. However, no further data was collected to reveal the reasons behind the ratings. Figure 5.17 shows the plots of the age of participants and their ratings in three post-test questions. While the available data shows strong correlations between the participants' age and their responses to the two questions, I want to point out that data comes from a relatively smaller sample size.



(a) Plot showing the relationship between the age of the participants and their ratings for "Did you like *Smart Motor*?"



(b) Plot showing the relationship between the age of the participants "Would you use *Smart Motor* again?"



(c) Plot showing the relationship between the age of the participants "Will you tell your friends about *Smart Motors*?"

Figure 5.17: Plot showing Age of the participants and their ratings the three post-test questions and best fitting line.

Table 5.8: Table showing the results of Spearman Correlation test between age and post-test survey answers

Question	Spearman Correlation	p-value	Interpretation
Did you like *Smart Motors*?	-0.542895	0.009033	significant negative correlation
Would you use *Smart Motor* again?	-0.589071	0.003919	significant negative correlation
Will you tell your friends about *Smart Motors*?	-0.166940	0.457756	no significant correlation

The test uncovered some issues with *Smart Motors* and the instructional video. First, most participants needed to be reminded of the presence of the *nav* button. Since the design I used in the test had *nav* buttons on the side and were made out of wood, there was no texture or visual information to indicate the presence and function of the buttons. Similarly, there were some issues with the icons on the screen. We used graphics instead of text to make it accessible for users who couldn't read because of language or age. For most of the participants, icons made sense - the ✚ icon meant "Add", ✖ meant "Delete" and ▶ meant play - as expected. However, some participants had to discover their meaning by playing around with the *selection* button, and some needed some hints. The other issue was that due to the poorly placed reset functions in the code, some *selection* button presses were ignored by the motor. This resulted in some difficulty during Activities 1 and 2, where the participants worked independently to discover the features of *Smart Motors*. I had to intervene, suggesting they press the button harder or multiple

times and look for cues like the motor shaking, dots appearing or disappearing on the screen, and the screen changing the contrast. Using plastic geared servo motors to reduce the overall price of the kit also caused some issues because of the broken and stuck gears. These pain points and sources of errors identified during the test will help improve the user interaction and experience in the next iteration.

5.6 Conclusion and Implications

In this chapter, I presented the usability test findings with *Smart Motors* V3. I tested the *Smart Motor* with 22 participants from 7 to 15 years old. Although my initial plan was to collect data from 30 participants - 3 from each age - there were cancellations and no-shows due to unforeseen and undisclosed reasons. However, I think the data from the 22 participants were rich and revealed many interesting details about the *Smart Motors*. First, the discoverability of features as a feature of *Smart Motor* indicates its ease of use, both hardware and the UI. With minimal instructions and occasional comments, almost all the participants could learn how to use *Smart Motors* and use it to create projects that were meaningful to them. The participants were satisfied with their experience, as shown by their post-test survey, where they rated the likeability, intention to reuse, and intention to recommend this to a friend.

Overall, all the participants were able to discover the *play* feature of the *Smart Motor*; some needed some help while others navigated their way to the discovery. The discoverability of the *play* feature for all ages means that pre-trained *Smart Motors* can be used in classrooms with younger users where the motor needs to move in a certain predictable way and do not need *training*.

Similarly, some participants could figure out how to *train* the *Smart Motor* right

away, while some needed some guidance. The transition of age around which they seemed to be able to figure out *training* on their own was around ten years old. This could potentially be explained by the cognitive development in children around that age and through their prior experience of using Cartesian coordinate systems in their schools and their experience of thinking in terms of inputs and outputs [94].

Evaluating the challenges the younger participants faced and the support that helped them overcome the challenges shows that with minimal instructions, either in video or text format, explaining the location of the buttons and the meanings of the icons more clearly can significantly improve the discoverability of the *Smart Motor* features.

All participants had prior experience with LEGO®, which must have helped them with the build. I chose LEGO® as I expected participants to have some LEGO® experience, and with that, I could reduce the variability in data. It would be interesting to conduct this test with the found materials and how that would impact the nature of the projects built in Activity 4.

For the future test, it would be interesting to test this with even younger participants and see how they make sense of the data. It would also be interesting to conduct a similar study with more participants to develop a clearer picture of the impact of age on their ability to discover and understand the functionality of *Smart Motors*. I am also curious to run this test with participants without LEGO® or robotics experience. Similarly, adding a logging system to monitor what buttons they press and in what order can reveal their learning process and how they make decisions.

Chapter 6

Investigating Characteristics of Playful Learning Experiences with *Smart Motors*

6.1 Introduction

In this chapter, I will analyze the characteristics of a playful learning experience while engaging with *Smart Motors*. Using The LEGO Foundation's Learning through Play Experience Tool, I will analyze the experience of three *Smart Motors* users engaged in a play-based activity. One of the purposes behind developing *Smart Motors* was to introduce robotics to children using a playful approach. The results from this analysis will help teachers seeking to introduce a playful approach in their classroom with robotics to decide what aspects of play they can improve and enhance with *Smart Motors*.

6.2 Acknowledgements

I want to acknowledge William Church from CRCS for his help in leading the workshops, taking notes, analyzing the data, and sharing his insights. I would also like to thank Kevin Lavigne from Hanover High School for allowing us to work with his students, Erin Glocke for putting together the curriculum used in the workshops, and Aengus Kennedy and Noah Saxenian for supporting the workshops.

6.3 Introduction to Characteristics of Playful Learning Experience

Playful learning has a universal appeal and resonates with learners of different ages in various educational contexts. It helps people with different learning styles to learn in a fun and engaging way [95, 96, 97] and has thus attracted a lot of attention in both early childhood as well as adult education [98, 99, 36]. This approach leverages innate human qualities like curiosity and creativity to facilitate learning in an engaging and intrinsically motivating manner. Educators have employed different play styles- from open, self-directed play to more constrained designed challenges [100]. Despite the nature of play involved, playful learning immerses learners in the activity where they experience and find personal meaning. Similarly, the materials used in playful learning approaches vary greatly, too. These materials range from everyday objects (found materials) to computers and are used to teach a wide variety of topics, like literacy, history, and STEM [101, 102, 88]. Evidence shows that playful learning happens through experiences that are joyful, actively engaging, meaningful, iterative, and socially interactive [37]. In this chapter, I will explore how a play-based activity with *Smart Motors* can support these experiences.

6.4 Methodology

I will use the data from an activity in a workshop I explained in detail in the third study in Chapter 4. The activity was part of a three-session play-based activity designed to introduce and implement *Smart Motors*. I used the data from the second session of Activity 1 with high school seniors in the Chemistry and Physics Projects for Seniors (CAPPS) course, where they learned to use *Smart Motors*. The goal for this session was for the participants to learn to use and implement *Smart Motors* through demonstration and practice. They were asked to design and build a "hello world" waving mechanism with LEGO® pieces and a *Smart Motor* that operated by manipulating the light sensors. All participants were given a *Smart Motor* to train and build the mechanism. They were asked to work individually but could combine their mechanisms to build a larger waving structure. The participants could use both position control (SM1 type) and speed control (SM2 type) *Smart Motors*.

6.4.1 Data Collection

All the sessions were recorded in video and audio. Cameras and microphones were set up at each desk to capture the group discussion and activities. Transcripts were generated from the discussion in all three sessions. In addition, researchers took field notes during the workshops. The build time for the second session was 30 minutes. I analyzed data from three participants: Tim, Jason, and Keshav's (pseudonyms) from Group 1. Tim, Jason, and Keshav worked independently but discussed and shared ideas and were always visible on camera, making data transcription possible.

6.4.2 Data Analysis

To analyze the characteristics of playful experience, we used the Learning through Play Experience Tool developed by The LEGO Foundation [103]. Video data from session two were transcribed in two-minute chunks for all three participants. For each two-minute section of the activities, the data was coded into one of the seven states of play for characteristics of a playful learning experience. The states of play given by the experience tool are Non-Play, Waiting, Passive, Exploring, Owning, Recognizing, and Transferring. A rubric (shown in Figure 6.1) from the Learning through Play Experience Tool [104] was used to code the data. The participants' tone and body language were taken into account while coding. In the end, the trends of states of play were graphed and studied.

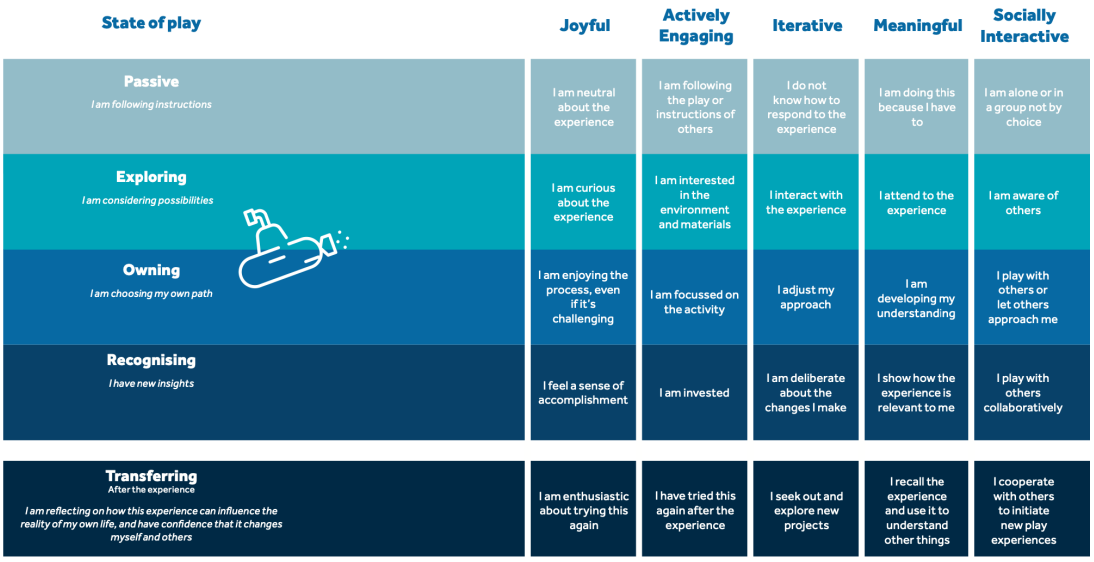


Figure 6.1: The LEGO Foundation's Learning through Play Experience Tool used to analyze the states of play in a play-based *Smart Motors* activity. [104]

6.5 Detailed Description of Participants' Activity

Tim, Jason, and Keshav followed similar paths in building the waving mechanism and exploring the *Smart Motors*. Before the activity, the instructors demonstrated and asked the participants to try training their SM1 type *Smart Motors*. All three participants could train the *Smart Motors* from the workshop instructor's demonstration without any problem.

At first, they all tried to build a simple waving mechanism using the SM1 type *Smart Motor*, where they trained it to wave back and forth. They were building with shared pieces from a single LEGO® SPIKE™ Prime Kit. This forced them to negotiate and share pieces while optimizing their designs. Once they had a simple proof of concept, they attempted to build complex creative mechanisms. During the build, a key moment was around the halfway mark when an assistant approached the group to check in and gave them the SM2 *Smart Motor*, which two participants used in their final design. I will describe each participant's journey through the design activity in the following sections.

6.5.1 Tim's unconventional waving mechanism

Tim wasted no time opening the kit, grabbing some LEGO® pieces and connecting them with his *Smart Motor*. The general mood during the activity was cheerful and carefree as he jokingly wondered aloud, "I don't know what a hand looks like," and "How many fingers does it have? Like, five?" while connecting and building a hand with five digits with the beams he had collected. When his teammates complained of a lack of pieces to build with, he said, "I think making a good-looking arm is not the goal of the activity" and urged his teammates to be "innovative" as he took pieces apart from his build for them to share and modified his arm to have three

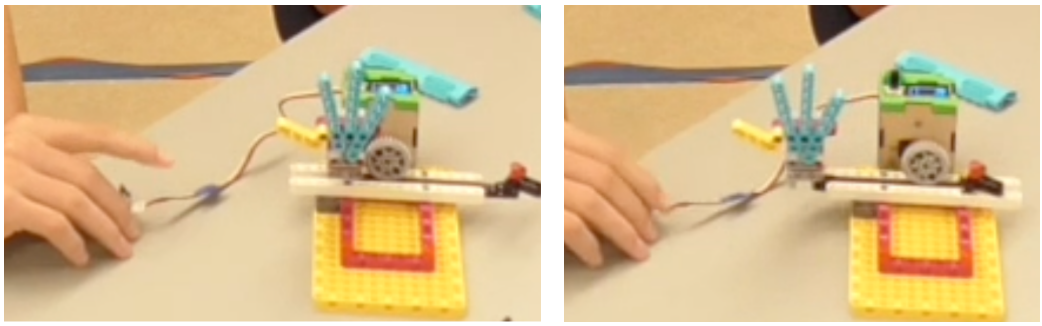
digits, showing his collaborative nature.

As he tested the arm, he wasn't satisfied with the way the arm rotated and moved, and Keshav, his teammate, agreed with his observation. Tim told Keshav about his goal of having the arm wave at him while he looked at the screen. He tested the motor's movement and light sensor's reading, noting how the motor reacted to the changes in light from his hand waving over it. Tim collected data on motor positions and light sensor readings, refining his tests by adjusting how quickly or slowly he moved his hand over the sensor and at what height (Figure 6.2). He realized the sensor needed slow movements to detect his hand shadows; otherwise, it would miss the readings, and the motor wouldn't move. He examined the situation and retrained the motor to move from one extreme to the other for multiple positions of his hand in front of the sensor. That way, the arm waved multiple times as he moved his hand closer to the sensor. While this was happening, Tim also paid attention to Keshav's and Jason's builds and engaged in friendly banters with them.



Figure 6.2: Tim testing how well the light sensor could read with his hand held at different heights and moved at different speeds.

Next, on the instructor's suggestion, Tim experimented with the SM2 *Smart Motor* and found that he could control the speed and direction of the motor. He said he wanted the arm to wave side-to-side instead of turning around a pivot (Figure 6.2). He built a rack and pinion style mechanism with a beam sliding under the wheel to accomplish this new goal and mounted his arm on the beam (Figures 6.3). He played around with different pieces and orientations to get the wheel touching the beam just enough to make it slide. With about four minutes remaining before the end of the activity, Tim was still finishing his build and had yet to train the motor. Tim hurried as the session neared its end, adjusting beams and testing the setup. Despite some confusion and last-minute adjustments, he managed to get the arm working just in time for the demonstration.



(a) Screenshot 1 (b) Screenshot 2

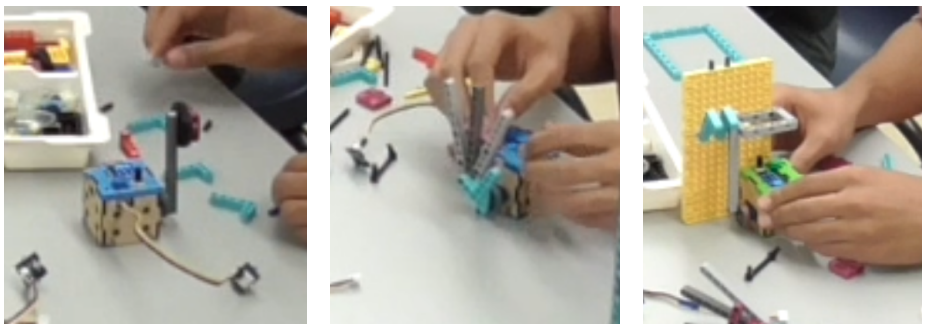
Figure 6.3: Screenshots of Tim's demonstration of his waving mechanism.

6.5.2 Jason's experimental designs

Jason wasn't as eager as Tim to get started as he had some questions that would impact his project. He asked, "What is our input?" Keshav responded, "Light." Jason wondered if they should make it complicated or keep it simple. He started exploring the materials while considering what kind of hand he would build. After some contemplation, he shared his idea with Keshav and gesticulated with his fingers how the fingers could curl in his design, which could be a wave. He initially

laughed at the complexity of the idea and began attaching LEGO® pieces to the *Smart Motor*.

First, Jason explored what he could do with gear and LEGO® beams and looked for specific types of pieces. He complained about the lack of pieces with Tim, who told him to be innovative. Jason spent some time observing Tim build, then engaged with the *Smart Motor*, attaching a beam and gear to the wheel (Figure 6.4a). He trained the motor for different light values but deleted them without testing. Returning to the building, he searched for pieces, again complaining about their scarcity. Jason kept an eye on Keshav's build as he searched for pieces, connected them, and detached them to connect in different configurations. He teased Keshav for building an "unappealing" design because it moved only left and right. He contemplated building his original complex design and shared his idea with Keshav. Initially, Keshav didn't react to his idea, but he finally responded "Yes, but it is hard to do". Next, Jason quickly built something that resembled what Tim had built with some fingers (Figure 6.4b). Tim approved!



(a) Exploration 1 with gears and beams.

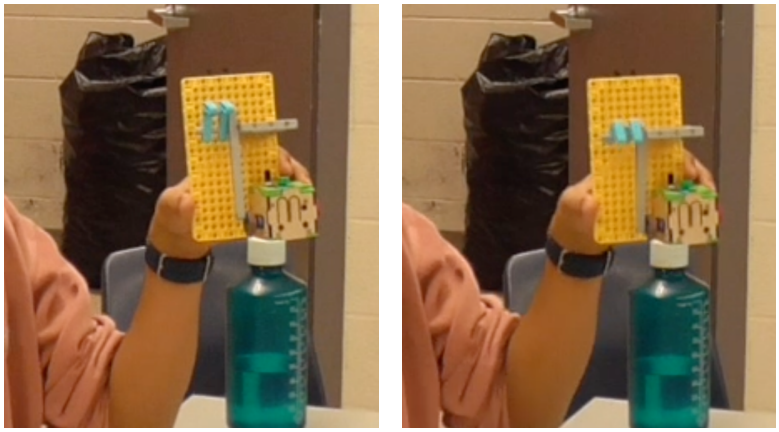
(b) Exploration 2 had fingers like a human hand.

(c) Exploration 3 with a single beam and SM2 *Smart Motor*.

Figure 6.4: Jason testing out different ways of constructing a waving mechanism.

Finally, with about 10 minutes remaining, Jason played with more beams, connecting them in different orientations to figure out how he would make them curl

down and open up, working on his original plan. With about 6 minutes remaining, he attached the yellow LEGO® plate to the side of the *Smart Motor* to mount the arm. Tim and Jason were both frantically looking for pieces that would fit correctly. As he scanned for the pieces, he looked frustrated when he said, "This is not going to work." But he persisted, and after some adjustments, he found a grey rectangular piece that solved his problem and ensured the arm could bend. He made final adjustments, replacing the yellow axle with a shorter black axle, and connected the arm to the motor wheel. As the motor spun, the arm moved up and down, curling as he had planned. He displayed his creation to Keshav and Tim, who gave approving gestures. Jason contemplated his next steps, making the motor spin faster, but the time was up. At this point, he realized he hadn't trained the motor yet and wasn't using any sensors.



(a) Screenshot 1 (b) Screenshot 2

Figure 6.5: Screenshots of Jason's demonstration of his second waving mechanism.

6.5.3 Keshav's Trident Hand

Keshav moved his chair closer to the team, assuming they were working as a group, but Tim and Jason confirmed they were working alone. The instructor clarified that they are working independently but could collaborate on ideas. Jason

and Keshav discussed inputs, and Keshav started attaching LEGO® pieces while looking around. He brainstormed with Jason as they built.

Keshav began constructing what looked like a claw with two curved LEGO® beams. They all searched for pieces to use, as they had only one set of materials for three. Keshav's creation started resembling a trident. He occasionally observed Tim and Jason's progress. He tried to attach his trident-like arm to the motor and asked, "Does this look like a hand?" He struggled to find the right pieces to connect the beam to the wheel. Jason complained to Tim on Keshav's behalf.

Tim and Keshav discussed how the arm would move when attached to the motor, with Keshav demonstrating how it would wave. Keshav continued searching for LEGO® pieces and moved the motor with the potentiometer, causing the arm to fall off. Jason found the movement "cute," to which Keshav responded, "Hey, it gets the job done." He attempted to mount the arm properly and continued testing.

Keshav attached the arm to the motor and moved it with the potentiometer to test how it moved. Jason commented that the jerky movements of the motors were "unappealing". Keshav defended the movements as "robot-like". He added more LEGO® pieces to his arm and told Jason, "Look, it looks pretty handish.". Keshav then trained the motor to go to two positions for two light sensor readings. He placed his finger over the light sensor to test whether the motor worked.

When the assistant came to check in and told them they could use a different motor, Keshav was the first to figure out that it was speed-based. He noticed the motors were strong enough to pull the rubber bands for, presumably, a different project. Tim and Jason used the two available SM2 motors, so Keshav started experimenting with some gears. He mounted them at 90 degrees to build a right-angled transmission (Figure 6.6). He didn't complete the build, but it looked

like he was trying to improvise a new waving mechanism. When the instructor informed them they had four minutes remaining, Keshav stopped his exploration of the gears, reconnected his arm to the motor, tested it, and got ready for sharing (Figure 6.7).



Figure 6.6: Keshav spent a few minutes examining how to build a waving hand using two bevel gears.



(a) Screenshot 1 (b) Screenshot 2

Figure 6.7: Screenshots of Keshav's demonstration of his waving mechanism.

6.6 States of Experiences

Using the rubric from the Learning through Play Experience Tool (Figure. 6.1), the data were coded for the three participants. All coded data are presented in

Tables E.1, E.2, and E.3 for Tim, Jason, and Keshav, respectively. The states of play from the coded data are presented in Figures 6.8, 6.9, and 6.10 for Tim, Jason, and Keshav, respectively. In the figures showing the trend of play, each box represents a two-minute segment of the data, and the highlighted box indicates the most prominent state of play in that segment. The graphs from top to bottom for each participant, as indicated in the illustrations, are Joyful, Actively Engaging, Iterative, Meaningful, and Socially Engaging, respectively.

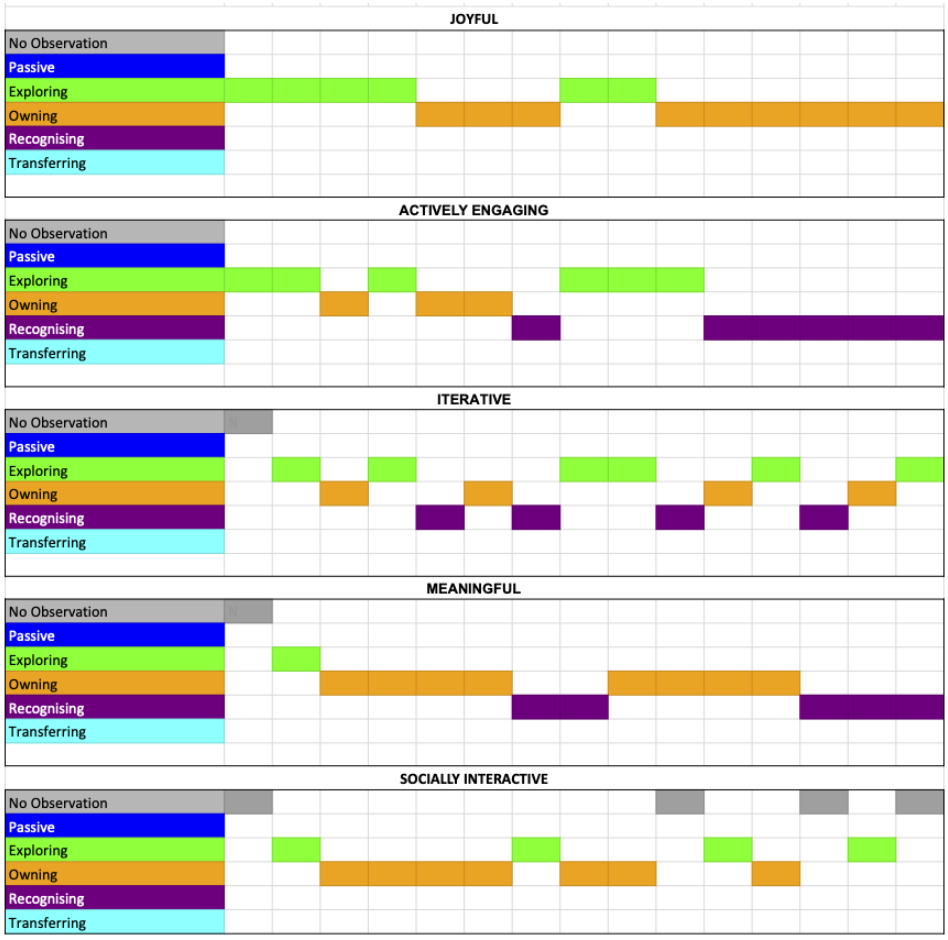


Figure 6.8: Graph showing how Tim transitioned through various states for each characteristic of the playful learning experience.

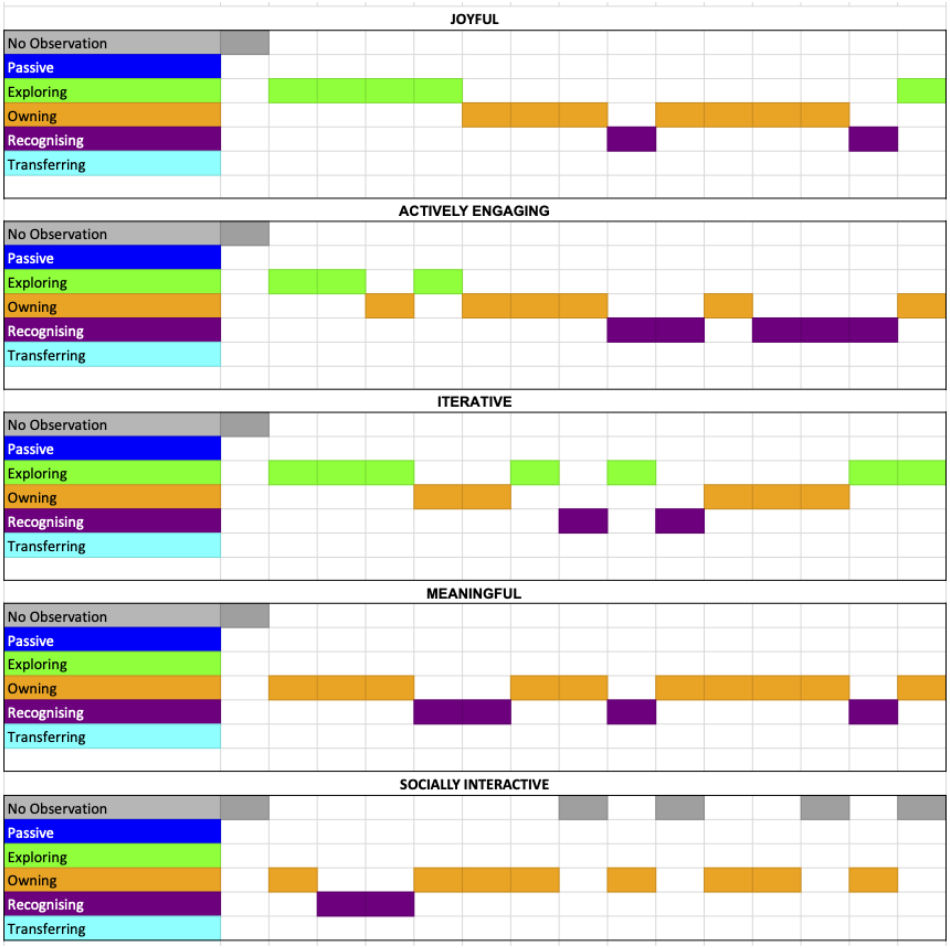


Figure 6.9: Graph showing how Jason transitioned through various states for each characteristic of the playful learning experience.

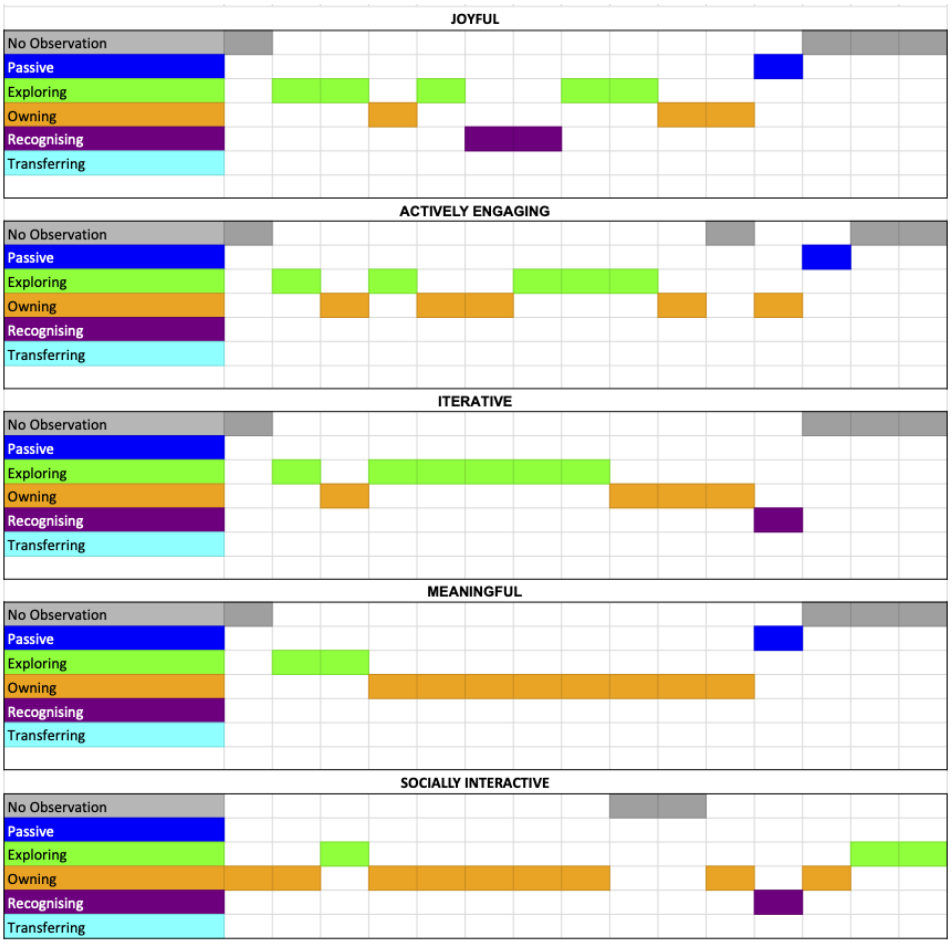


Figure 6.10: Graph showing how Keshav transitioned through various states for each characteristic of the playful learning experience.

6.7 Analysis of the trends

Analyzing the play trends from the figures, we can observe how the participants moved across the states at different stages of the project. We noticed the participants almost always start at the Exploring state, move to Owning, and transition to Recognizing states before returning to Exploring and Owning states. This is consistent with the literature. In the sections below, I will discuss each characteristic of the playful learning experience and what it means to the *Smart Motors* based activities.

6.7.1 Joyful

States of joyful characteristics are challenging to observe because sometimes they are not expressed clearly. However, we can infer the various states of Joyful from clues like body language, participation level, discussion with teammates, etc. In the data, I analyzed the participants who mostly traversed the Exploring and Owning states. Jason and Keshav occasionally reached the depths of Recognizing. Tim had a sustained period in the Exploring state as he tried to figure out how the pieces went together and what his project would look like. He had two similar transitions from Exploring to Owning, corresponding to the two explorations he became caught up in. The first exploration led to the simple-looking hand, with which he tested the sensor's sensitivity and motor response.

Similarly, Jason had similar transitions. Initially, he spent a fair amount of time exploring the materials and showing curiosity about the projects he could build. Once he built his first arm, indicated by the first Recognizing state, he became confident enough to explore and continue plowing through the challenges, eventually succeeding and reaching the second Recognizing. In both cases, he showed pleasure and a sense of accomplishment.

Keshav's trend showed intermittent transitions. He exhibited a sense of accomplishment early on. After that, he returned to Exploring and Owning states, but the experience couldn't mature, and he transitioned to Passive and discontinued states towards the end after a 4-minute remaining call. There could be two reasons: 1. He had completed the task and didn't feel the need to build another. 2. He didn't have enough time to continue exploring the new path.

Through the experience of three participants, we observed significant moments of joy where participants persisted through confusion and frustration and emerged

with a successful build.

6.7.2 Actively Engaging

Tim entered the activity in the Exploring state immediately while his teammates were still waiting for instructions. Two moments in Tim's data can be highlighted with the play trend. The first was when he was completely invested in getting the sensor and motor to behave the way he wanted, which was short-lived as he figured out how to solve it quickly. The second was towards the beginning of the second half when he started exploring the SM2 *Smart Motor*. He was completely invested in building an out-of-the-box build with the SM2 for a sustained period till the end of the build time.

Jason had a similar trend, with two transitions to Recognizing state. The first one was when he became invested in making something work as soon as possible so that, presumably, he could spend more time trying to build his original idea and not risk failure.

Keshav transitioned between Exploring and Owning states but never entered the Recognizing state as he wasn't as invested in the build as Tim and Jason. He was focused on building his arm and getting it to work but faced no obstacles to overcome.

All three participants were actively engaged with *Smart Motors*, whether trying to get the sensors to work properly or getting the attachments right. It was remarkable to see how engaged the participants were to such a simple prompt, which they accomplished in half the time but pushed further to explore and engage more deeply with the experience.

6.7.3 Iterative

The trend of states clearly shows that Tim underwent many quick, deliberate changes in his designs. From an arm that waved for two values of lights to the arm that waved multiple times as the hand approached the sensor and to a unique build with a rack and pinion mechanism, Tim quickly and frequently reached the depths of iteration. In the case of Jason, he had a design on his mind that he kept coming back to. But he also wanted to have something as a backup. So, he experimented and iterated on two designs almost simultaneously. Keshav mostly repeated the same things and encountered no issues requiring him to pivot until the end. He discovered that the bevel gear mechanism he was trying would take longer than he had, so he deliberately abandoned the build and rebuilt his original design.

Two participants went through the iterations more frequently. Iterative characteristics might depend on the participant's building style—planning ahead vs. experimenting—and the complexity of the design. More complex designs would require more iterations.

6.7.4 Meaningful

The analysis of data for Meaningful showed that the participants were guided mainly by the activity's goal. All instances of their build activity were to fulfill the prompt's challenge. Therefore, all three participants were mainly in the Owning state, where they developed their understanding of the system and showed that their actions were goal-directed. They would also talk about what they were doing and trying to accomplish. For example, Jason regularly told Keshav how he wanted to investigate the curling mechanism for waving, which he accomplished in the end. Similarly, Tim didn't only want to build a simple mechanism but wanted something

complex. Keshav, similarly, gave meaning to his arm's jerkiness by saying that's how robots move. These instances showed how the participants ascribed meanings to their build - in Tim's and Jason's case, they wanted to accomplish the task and build something complex and unique, and in Keshav's case, how a simple build could fulfill the ultimate goal of the exercise.

6.7.5 Socially Interactive

The participants worked independently but shared the same kit to build. However, their social interaction was more than sharing the pieces. They constantly shared ideas, gave feedback, checked for validation, and complimented each other's designs. Since they were working individually, there were moments of No Observation when they withdrew from their teammates and focused on their explorations. Tim's social interactions were mostly limited to validating his teammates' designs when they demonstrated him or asked for his opinion. He once engaged with Keshav to share his ideas and get his thoughts. So, he never fully engaged with them to collaborate and help the teammates. Jason and Keshav had similar trends, except they reached the depths of the Recognizing state at least once. Jason negotiated with Tim on how he should share pieces with the rest of the group and voiced his concerns on Keshav's behalf. Keshav assisted Jason in figuring out how he could get out of *play* mode without being asked to. Keshav regularly paid attention, showed awareness of his teammates' activities, and was quick to offer thoughts and feedback.

6.8 Discussion

The learning objective for this "Hello World" activity was for the participants to learn how to use *Smart Motor* and implement it in an open-ended project. As

discussed in the previous chapter (Chapter 4), the students in this workshop and another workshop with younger participants could fulfill the objectives at different paces and build projects with various levels of complexity in terms of mechanisms and numbers of *Smart Motors* used.

Observation and analysis of the participants' activities showed evidence of all five characteristics of a playful learning experience. Using the Experience Tool, we saw how, for each of the characteristics, the participants' experience transitioned from one state to another throughout the activity. In a playful learning activity, the goal for the participants is not to reach the deepest levels as fast as possible or to stay there for the entire duration of the activity [37]. The recurring pattern we observed was that they entered the experience by considering many solution paths through exploration. After exploring the possibilities, they formed an idea and dipped into the Owning state ("I am choosing my own paths") until dipping further into the Recognizing state of play ("I have new insights"). This can be seen in the graphs in Figures E.1, E.2, and E.3 where the participants reached the deeper states after first reaching and experiencing the shallower states and did not stay in the deeper states of play for a prolonged duration. Instead, they shifted back to shallower states to generate and experiment with more ideas from the insights developed in the deeper states. I will discuss the analysis of the observations below:

- *The playful learning experiences with Smart Motors were dynamic:*

  The cyclical pattern of experience between Exploring, Owning, and Recognizing states suggests a natural progression in learning and creativity. This aligns with constructivist theories, where learners build upon their experiences through continuous cycles of exploration, reflection, and application. Because of the possibilities of unique and diverse solutions and opportunities to make continuous improvements with *Smart Motors*, the

states of participants' experience for all five characteristics of playful learning experience were dynamic.

- *There were few to none Passive states:*

  Passive states were only observed towards the end of the activity when the participant had achieved the activity goal and didn't have enough time to work on a new idea or improve. This can also be interpreted as a success for the tool and activity, as all participants were successful towards or just before the end.

- *Build up to a joyful experience goes through phases of struggle and persistence:*

  Since joy is intrinsically connected with learning [105, 106], it is paramount that students experience joy in the activity. Sometimes, joy can be misinterpreted when a student is engaged in a frustrating challenge as being miserable. However, learning happens only when they persist through frustration and distraction. Therefore, the Experience Tool puts the state where the participant persists through a challenging phase as a shallower depth of the Joyful experience. We can see how all three participants have stayed in the Exploring and Owning states most of the time, persisting through the challenge and occasionally exhibiting a sense of accomplishment. The low barrier and high ceiling nature of *Smart Motors* allowed all three participants to persist without giving up, as they saw opportunities to become successful, following completely different paths.

- *All three participants were actively engaged:*

  All participants were actively engaged throughout the activity, and two participants experienced a deeper level of active engagement towards the end

as they were trying something new and didn't have enough time to afford to lose attention. This could be attributed to the participants' nature and activity context. But we can also attribute this to the easy-to-use and versatile nature of *Smart Motors* that allowed the participants to have the confidence to push through, even when the time was running out. Overall, play-based activity with *Smart Motors* provided various levels of engagement and rarely a Passive moment during the activity.

- *There were several quick iterations in a short amount of time:* Iteration is one of the most important characteristics of an engineering design process [107, 108]. The graphs show the quick succession of iteration for two participants. They always started in the Exploring state, either moved to the Owning state, where they tweaked their approach, or moved to the Recognizing state, where they realized their process would not work and needed an overhaul. In Tim's and Jason's cases, the Recognizing state was always followed by shallower states where they experimented and adjusted their approach. In Keshav's case, he didn't iterate as often as the others, and so in the end, when he reached Recognizing, he resorted to the tried and tested build, probably because of lack of time. A deeper look at the kinds of things the participants were iterating on revealed that they mainly were iterating on the build and not on *training* the *Smart Motor*.

- *Participants mainly were focused on goal-oriented actions:* The graph of states for the Meaningful experience shows that the participants gave meaning to their build and stayed focused on their goals throughout the exercise. The participants spent most of their time in the Owning state, where they showed evidence of their actions being goal-oriented. In a few instances, they discovered something about the design, the tool, or the experience that added

value to their personal goals. Since the participants set the goals, their attitude towards the activity could have been impacted. The open-endedness of the activity could have allowed the participants to find personal significance in their work, which drove deeper engagement and learning.

- *Lots of social interaction while working on independent projects:*

  The participants' willingness to engage in discussion and negotiation and seek approval and validation from their teammates while working on personally meaningful independent tasks was remarkable. The graphs in section 6.6 show the frequent interactions between teammates at the idea-sharing level and a few where they cooperated to complete the task and negotiated the rules about sharing the materials. Despite the independent nature of the activity, the graphs show the presence of collaboration and communication.

Thus, we observed that a play-based activity with *Smart Motor* facilitates all the five characteristics of a playful learning experience: Joyful, Actively Engaging, Iterative, Meaningful, and Socially Interactive. The transitions of states of play suggest the dynamic nature of their experience through the exercise. I must, however, acknowledge that there were a few variables at play, like the nature of the activity, the age of the participants, and the number of participants working together in a group. Still, I argue that some of the attributes of playful learning would show similar trends in various other situations. Chapters 4 and 5 have shown that *Smart Motors* have discoverability as a feature and, therefore, are teachable with minimal instructions and some explorations. They also have a high success rate, meaning users feel they can build the projects they want with *Smart Motors* with high accuracy. In addition to that, *Smart Motors* affords solution diversity or they afford multiple design solutions as the users can train them. These attributes

of *Smart Motors* mean that the users either gain mastery over *Smart Motors* quickly or at least know that they can implement it quickly with some help, allowing the participants to focus on the project with confidence. This confidence of success allows the users to venture into complex builds, which we have noticed in Chapter 4 for different ages and activities. This means they can engage, iterate, and focus on building personally meaningful projects when allowed and feel accomplished in the activities regardless of age as long as they can find meaning in the projects.

How can teachers use Smart Motors to support playful learning in their classroom?

Teachers looking at enhancing a certain attribute in their students' experience can tailor their activity with *Smart Motors* to align with their objective. For example, to encourage deeper states of Iterative characteristics, they can create flexible, open-ended tasks that encourage experimentation and iteration. Similarly, to encourage deeper states in Active Engagement, their activity could allow participants autonomy to explore their interests and engage deeply with the materials. This would also encourage them to build meaningful projects. We have found in similar workshops that participants get help from their teammates to learn how to use *Smart Motors* more than they do from the instructors. They also share ideas, show their progress, and ask for materials with their friends, even when unprompted.

6.9 Reflection on Learning through Play Experience Tool

The LEGO Foundation's Learning through Play Experience Tool allowed us to examine the data in minute detail. Analyzing and labeling data provided a way to quantify students' experiences and share and discuss the data by capturing important moments in the experience. Comparing the changes in the participants'

states of experience allowed us to create a complete picture of the classroom experience at any given time.

While it is designed for instructors to evaluate their lessons iteratively to improve students' experiences, it can also be used as a research tool. The data can be used for quantitative and qualitative analysis. Insights on the number of iterations during an experience and the duration of the participant's various states can be quantitatively analyzed. Similarly, transitions within Actively Engaging, Joyful, and Meaningful characteristics and the nature of social interaction within the group can provide important insights into the nature of the activity, participants' psychology on perseverance, and group dynamics on collaboration. In my experience, reviewing the graph of states of play provided reassurance of my observations from the data.

I found that there are a couple of things that researchers should pay attention to in order to utilize this tool fully. First, they should consider biases in their data analysis and labeling. In two minutes, the students can go through lots of experiences, and while the tool suggests using the most prominent of those experiences, our biases might lead us to label the data in a certain way. Therefore, multiple raters should label the data by defining how they code the data in detail. Another possible source of error and inconsistency could be how the data is divided into 2-minute chunks. All coders should agree on the start and end times of the two-minute chunks for the labeling. Data coding requires the researchers to look not only at the transcriptions but also at the physical behavior of the participants. Therefore, it is best to use multiple cameras capturing participants' actions from different angles and microphones to pick up conversations accurately. This process takes a lot of time and requires multiple passes to label the data. Discussing and setting guides on how the data is divided into chunks, what constitutes an

experience, and deciding how to label data for contentious segments can produce a reliable result.

6.10 Conclusion

Smart Motors is a low-cost trainable robotics tool that can be implemented in a play-based activity for playful learning. In this chapter, I used data from one of the play-based activities to introduce and implement *Smart Motors* in an open-ended design challenge. We used position control (SM1) and speed control (SM2) type of *Smart Motors* V3. The participants had to learn how to use the *Smart Motor* and develop a build or mechanism to emulate a waving gesture. By carefully coding the data of three participants from the 30-minute activity into 2-minute chunks for seven states of five characteristics of the playful learning experience, we plotted and analyzed the trend of the states. We found that the short activity had features of all five characteristics of the playful learning experience. We further looked into the graph to understand the transitions and flow of states within each characteristic. We found that students were exhibiting playful learning experiences and reaching the deeper ends of each characteristic. We looked at the graphs of the characteristics of the playful learning experience. We analyzed what it meant and how *Smart Motor* played a role and found out that the *Smart Motors'* unique characteristics like easy-to-use, low-barrier to entry, high-ceiling of opportunity, the possibility for multiple solutions through training afforded the students to engage deeply, iterate frequently and persist through the challenges to create personally meaningful builds. Even though they were working independently, the design activity allowed them to engage collaboratively in discussions, banters, and supportive roles.

Chapter 7

Discussion, Stories of Collaboration, Future Work and Conclusion

In this concluding chapter, I will revisit the main points of discussion in the preceding chapters to answer the research questions I posed in Chapter 1. Then, I will share the stories of collaboration with our partners in Brazil [109] and Nepal in developing local versions of *Smart Motors*, training teachers to use them in classrooms, and developing lessons to teach engineering, science, math, and arts. It became apparent early on that one of the ways to make an impact with *Smart Motors* and increase access is by using locally available materials and expertise in developing versions of *Smart Motors* and peripherals that suit the local context. Then, I will briefly discuss the next steps in our exploration towards expanding the reach for *Smart Motors* and upgrades we want to make to our current designs. Finally, I will conclude the dissertation with conclusions and learnings we had over almost four years of development and testing the *Smart Motors*.

7.1 Discussion of Research Questions

7.1.1 How can we develop a $30 trainable robotics kit for a classroom with low resources?

In this dissertation, I described how we developed an affordable and accessible educational robotics kit for classrooms with limited resources called *Smart Motors*, allowing users to integrate technology into their learning without requiring extensive expertise. In Chapter 3, I discussed the prototypes and how, with each iteration, we improved the features and lowered the cost to eventually develop an under $30 *Smart Motor* V3. By eliminating the need for a computer to program the *Smart Motor*, we reduced the overall cost and lowered the barriers to entry in the 7-15 age range. In Chapter 5, I showed that the robotics kit we developed was successful in helping users build different robotics projects, and they were rated highly by the users, and that the idea of training a robot instead of programming was intuitive for most users in the 7-15 age range. In Chapter 4, I showed that *Smart Motors* can be used in classroom settings on various topics with a wide range of students. While some prototypes didn't fulfill the $30 cost constraint strictly, they showed the possibility of using robots to successfully teach various topics that don't require a computer or the internet. By making the instructions to construct and customize all *Smart Motors* versions, we have opened a way to enable skilled teachers to adapt and modify *Smart Motors* to lower the cost further and increase their functionality.

Some prototypes, not discussed in Chapter 3, like the ones that use Arduino, micro:bits, LEGO® robotics kits, which many schools may already own, are also shared with the public. The overall price can be lowered by using the existing

platforms to construct *Smart Motors* by following the instructions[1].

7.1.2 What are some ways *Smart Motors* can be integrated into the classroom to support STEM education? What results emerge through this integration?

To reiterate the main points from Chapter 4 *Smart Motors* can be used by integrating them in open-ended engineering design challenges, arts and storytelling activities, and science investigation activities. The open-ended engineering design challenges can be combined with literacy and engineering frameworks like Novel Engineering, where the students can apply and enhance their engineering skills and engage deeply with literature, or with challenges like rube-goldberg machines [110], where the students can engage in playful experimentation of materials and physical properties, and practice working in groups. They can also be used to talk about culture, lifestyle, history, and pressing issues like the environment through storytelling and art. Using a wide range of sensors supported by *Smart Motors* like humidity and moisture sensors, light sensors, temperature sensors, and distance sensors, and building projects with them allows the users to investigate the different material properties like moisture content in air or soil, propagation path of light, or transmissibility of materials, heat content of a material, and other relevant physical properties. In addition, *Smart Motors* can also be used to demonstrate and discuss the physical implementation of machine learning concepts and guide the discussion of issues like ethics and safety with machine learning and artificial intelligence.

To answer the second part of the question, below are some of the results that emerged through the integration of *Smart Motors* in STEM classrooms:

1. Solution Diversity: Students demonstrated various unique and adaptable solutions using *Smart Motors*.

[1] http://smartmotors.ai

2. High Engagement: Students remained deeply engaged, collaborating and refining their designs throughout the activities.
3. Creativity and Innovation: Smart Motors enabled students to create inventive and imaginative solutions.
4. Risk-Taking and Complex Designs: The low risk of failure encouraged students to attempt complex designs and iterate confidently.
5. Enhanced Collaboration and Communication: Group projects improved student teamwork and communication skills.
6. Self-Directed and Independent Learning: Students independently explored and pushed the boundaries of their initial designs.
7. Rich Discussions and Critical Thinking: Students engaged in meaningful discussions, enhancing their critical thinking and understanding.
8. Application of Interdisciplinary Knowledge: Students applied knowledge from various disciplines to enrich their projects.
9. Adaptability to Different Age Groups: *Smart Motors* were effective for students from second grade to high school, with varying levels of guidance needed.
10. Meaningful and Contextually Relevant Projects: Students created projects that were personally meaningful and relevant to their contexts.

7.1.3 What are some of the attributes of playful learning that *Smart Motors* facilitates in a play-based activity? What attributes emerge when users engage in a play-based activity with *Smart Motors*?

Analysis of the participants' data in a play-based activity with *Smart Motors* in Chapter 6 showed how the participants experienced playful learning stipulated by playful learning literature [37]. The participants' journey within each experience, namely, Joyful, Actively Engaging, Iterative, Meaningful, and Socially Engaging, revealed how *Smart Motors* based activity supports dynamic learning experiences, taking participants from shallower Exploring states where they explore the possibilities to deeper Recognizing states where they develop insights, with regular frequency. The properties of *Smart Motors*, such as being easy to use, having a low barrier to entry, and offering high potential for various solutions through training, allowed the students to engage deeply, iterate frequently, and persist through challenges to create personally meaningful designs. Even though they were working independently, the design activity allowed them to engage collaboratively in discussions and supportive roles.

7.2 Stories of Collaboration

As mentioned in the introductory chapter, the development of *Smart Motors* was part of The LEGO Foundation's Tech & Play initiative. Brazil and Nepal were two partner countries we worked with to bring a playful approach to integrating technology into classrooms. The purpose of this collaboration was to enable teachers and children to express themselves creatively through tinkering and robotics and provide them with the necessary skills to do so. In the following sections, I will discuss the efforts made by our partners in Brazil and Nepal in

developing *Smart Motors*. Most of this collaboration happened over Zoom and emails. In the summer of 2022, collaborators from Brail visited Tufts CEEO to collaborate and exchange ideas on improving *Smart Motor* designs and their use. Similarly, in the summer of 2022, I visited Nepal to run a teacher workshop and laid the groundwork for developing a Nepali version of *Smart Motors*. In November of 2022, I visited Brazil to attend the Festival of Invention and Creativity, where the public interacted with the Brazilian version of *Smart Motors*.

7.2.1 Acknowledgements

I want to acknowledge Dr. Eduardo Bento Pereira and his group from the Federal University of São João del-Rei (UFSJ) and Dr. André Peres and his group from the Federal Institute of Education, Science, and Technology of Rio Grande do Sul (IFRS) in Brazil, Dipeshwor Man Shrestha, Surya Gyawali and their team from Karkhana Samuha in Nepal and their teams for collaborating with Tufts Center for Engineering Education and Outreach (CEEO) in this project.

7.2.2 UFSJ/CyRoS, Brazil

The Center for Robotics and Assistive Technologies (CyRoS) at the Federal University of São João del-Rei (UFSJ) combines educational, innovation, and extension projects and research. The center focuses on project-based and play-based learning, with an emphasis on creative learning [111], tinkering [112], and STEAM education [113]. Before collaborating to develop *Smart Motors*, the group had already been exploring accessible technologies for Brazilian public schools and non-traditional learning environments by creating Arduino-based educational robotics tools such as Duinomaker[2]. DuinoMaker is an adaptation of

[2]https://www.duinomaker.org

ArduBlockly developed at UFSJ that enables users to code Arduino boards using a block-based language. The development of *Smart Motors* continued this effort.

The first effort from UFSJ was to explore building *Smart Motors* using existing Arduino kits in schools. They began by developing *Smart Motors* blocks in DuinoMaker to allow educators with access to Arduino-based robotics kits to convert them into *Smart Motors*. In the application, the users could select the ports for available sensors and motors, and it generates the code to convert the kit into a *Smart Motors* system (Figure 7.1). The teacher would only need one computer to upload the code onto the Arduino, which students could use without individual access to a computer. This would enable schools that do not have enough computers to support all students in gaining robotics experience.



Figure 7.1: DuinoMaker visual programming interface and example of an Arduino board-based kit assembled as a *Smart Motor*.

DuinoMaker blocks were useful and impactful in making *Smart Motors* available to students. However, it expected teachers to have some technical skills to set up the connections and find the right pins, which can be limiting in many cases. Therefore, the next step was to create a *SmartBox* version of *Smart Motors* using locally available materials like Arduino-based boards (Figure 7.2a).

In the first iteration of *SmartBox*, the users could map two sensor values to two different motor positions. This was sufficient for projects for beginner students, and it functioned as the low floor stipulated by the creative learning (CL) educational

approach. To accommodate students to explore more complex projects, the high ceiling, they developed another version of *SmartBox* with a display interface (Figure 7.2b) and vector blocks in DuinoMaker to allow more than two sensor-actuator pairings. The code and CAD files are available on a publicly shared Google Drive[3].



(a) Without display.

(b) With display.

Figure 7.2: *SmartBoxes*: Arduino Uno-based *Smart Motors*.

A team from UFSJ visited Tufts CEEO in June 2022 and collaborated on improving the fabrication techniques for the PCBs. Ten *SmartBoxes* based on the Arduino Uno were subsequently built and used at the Festival of Invention and Creativity (FIC) in November 2022 at UFSJ (Figure 7.3).

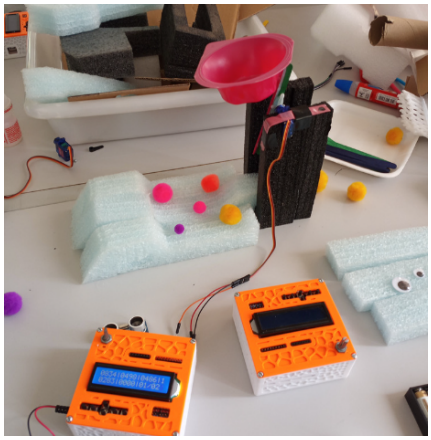


Figure 7.3: SmartBox presentation at Festival of Invention and Creativity in São João del-Rei, Brazil.

[3]bit.ly/3oqk3gk

7.2.3 IFRS/POALAB, Brazil

The Fab Lab POALAB, located at the Federal Institute of Education, Science, and Technology of Rio Grande do Sul (IFRS) on the Porto Alegre campus, serves as one of the Brazilian Creative Learning Network (BCLN) hubs. The lab focuses on digital fabrication and the creative learning approach, empowering the community to create technology-based solutions while engaging in learning.

Initially, researchers at IFRS explored local materials suitable for fabricating *Smart Motors*. They reached out to teachers to identify the robotics kits available in schools. It was found that most public schools in the Rio Grande do Sul state have robotics kits equipped with Arduino Uno boards, motors, wheels, and other electronic components, all of which were ideal for building *Smart Motors*. Realizing that building *Smart Motors* could also be an exceptional learning opportunity for electronics and programming teachers and students, they started developing two shields[4] geared towards this goal. The first shield was built with acrylic and copper adhesive that served as an Arduino Uno shield. The second shield was built using a phenolic board compatible with ESP8266-nodeMCU boards. The NodeMCU boards were also readily accessible to most schools at a low cost. The *Smart Motors* developed at IFRS using materials locally available in Brazil costs $16. As many schools already have many components required to build the system, this price can drop to $2-$4.

For the first shield with Arduino Uno, Tracks were marked, and holes were created on 3mm acrylic sheets using a laser cutter. A vinyl cutter was used to cut copper adhesive sheets to construct the PCB traces. Finally, the copper traces were taped on the acrylic sheet, and components were added and soldered. Figure 7.4

[4]https://github.com/poalab/smart_motors

shows the development of this first iteration with different materials and techniques. Figure 7.5 presents the final prototype with acrylic and copper adhesive tapes.

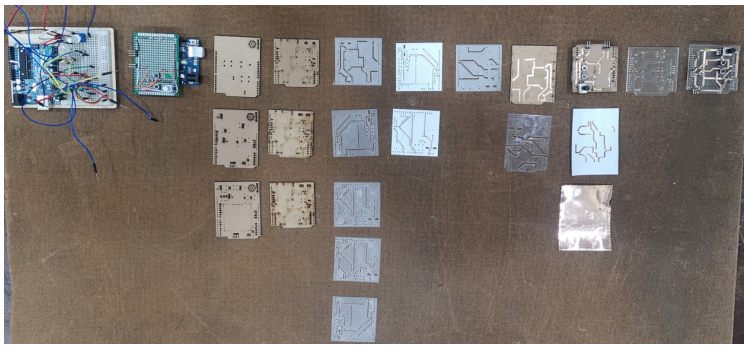


Figure 7.4: Picture showing the exploration of different materials and techniques to develop a *Smart Motor* shield for Arduino Uno.

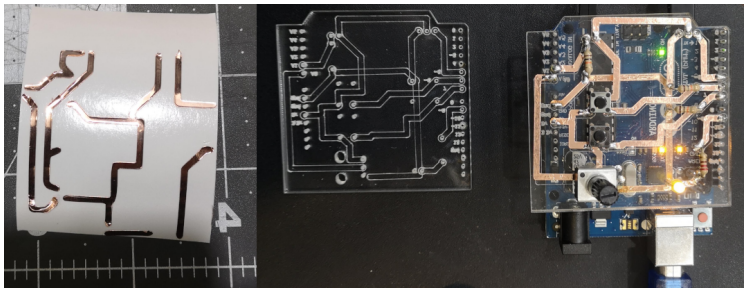
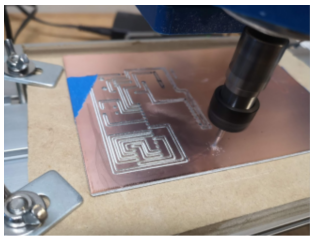
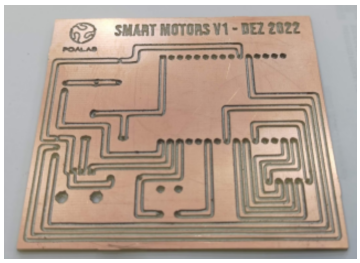


Figure 7.5: Final components of *Smart Motors* shield for Arduino Uno.

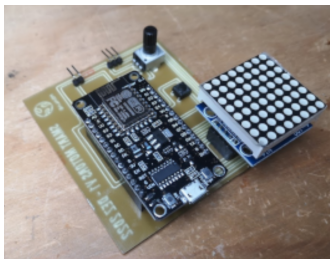
The shields for NodeMCU boards were made using a phenolic board and a milling machine. PCBs were created on phenolic boards with a copper surface by milling out to form traces (Figures 7.6a and 7.6b). The components were soldered and connected on the board, which included an 8x8 LED matrix display used to display information and an ESP-8266-nodeMCU board, as shown in Figure 7.6c. A research study was conducted using this prototype with teachers on using technology in classrooms [114].



(a) Milling process to build the PCB.



(b) PCB for NodeMCU *Smart Motor* shield.



(c) A complete *Smart Motor* shield with NodeMCU board.

Figure 7.6: Different stages to build a *Smart Motors* shield for NodeMCU board.

A team from IRFS visited Tufts CEEO in the summer of 2022, where they discussed circuit design strategies and explored various fabrication techniques. They also worked on refining the code for *Smart Motors*. During the visit by Tufts CEEO in November 2022 in Brazil, a discussion about the project with a group of Brazilian school teachers paved the path for an extension course at IFRS, which targeted teachers from robotics classes in public schools in Rio Grande do Sul (Figure 7.7). The course was taught in September 2023, and local science and makerspace teachers participated, where they learned about electronics and fabrication while building *Smart Motors*.



Figure 7.7: Meeting with teachers at POALAB.

7.2.4 Karkhana Samuha, Nepal

Karkhana Samuha is a non-profit organization based in Nepal that uses design thinking and results-based management that works in the innovative and inclusive education sector, among others[5]. Through innovation in technology and learning experiences, their work focuses on inclusive and equitable quality education. To bring technology that can be easily incorporated into existing classrooms, they investigated and explored a local version of *Smart Motor* [115] and developed a series of lesson plans to use in regular classrooms [116]. They based their design[6] on the *Smart Motors* V2.1 described in Chapter 3. They built 36 *Smart Motors* and distributed them among 12 teachers. They impacted 439 students over 98 classroom activities.

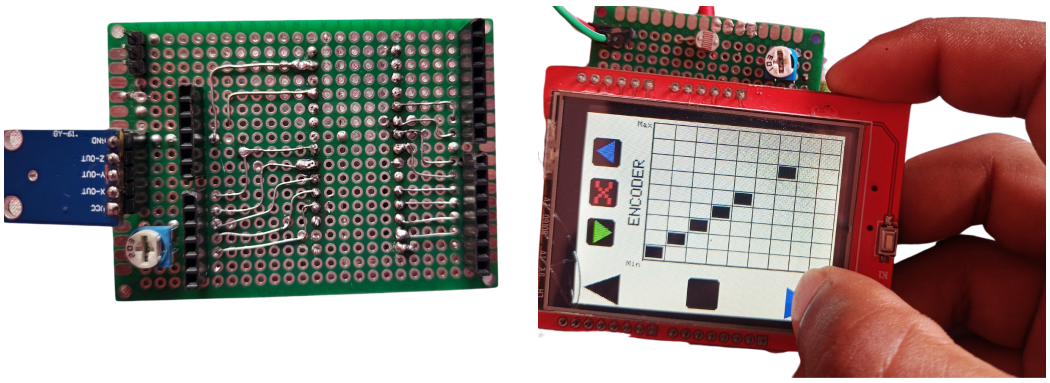
First, they ran a series of workshops with interested teachers on the *Smart Motors* V2.1 through science projects built using *Smart Motors* and started developing lesson plans. The teachers also built robotics projects with the *Smart Motors*. Trainers from Karkhana Samuha ran Novel Engineering activities with the teachers, incorporating *Smart Motors* to solve problems from a story from local Newa culture. Then, they gathered feedback from the students and teachers who had used *Smart Motors* and used the co-design process with the teachers to design a robotics-based lesson plan with the *Smart Motors*, which they got to implement with the local version of *Smart Motor*.

To design the local version, they started by exploring different materials and techniques to build a customized local version to reduce costs and improve the design. After several testing iterations with different display boards and microcontrollers, they settled on Arduino Nano and a 2.4-inch TFT touch display

[5]http://karkhanasamuha.org.np
[6]https://qrfy.io/r/KSSmartMotors

as main components.

After confirming they could find all the components locally, they began prototyping on matrix boards, as shown in Figure 7.8a, and started developing the user interface (Figure 7.8b). They opted to have their sensors plug into the board rather than soldering them onto the *Smart Motors* boards, based on feedback from teachers and students. They developed light sensors, variable controls using potentiometers, and motion sensors using accelerometers. They used SG90 servo motors as actuators. Additionally, they designed a battery pack to be used with the *Smart Motor* for uninterrupted operation during unpredictable and frequent power outages.



(a) Prototyping on matrix board.

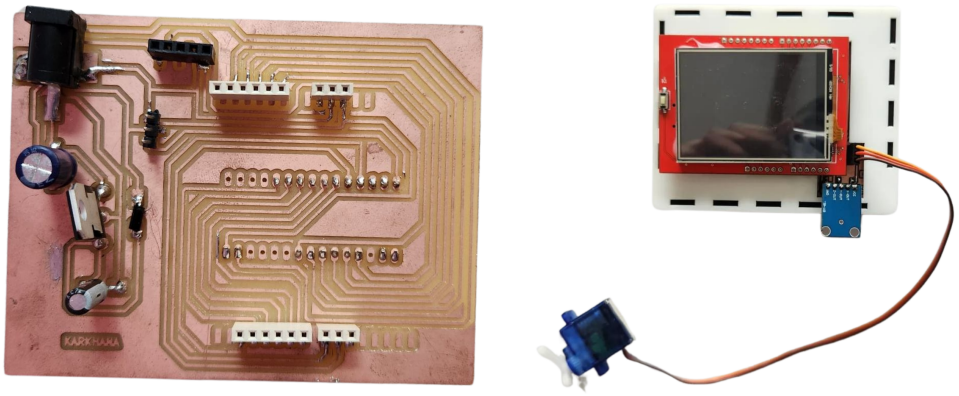
(b) Testing the UI on a TFT touch display.

Figure 7.8: Prototyping *Smart Motors* on matrix board using TFT touch display.

They partnered with a local FabLab[7] to manufacture the PCBs. Due to the limited capacity of the tools, they could only fabricate a single-layered PCB, which made the design bulkier than expected (Figure 7.9a). Finally, MDF boards were used to build the casing. The touch screen provided all the user interaction features and information on the training data and status. Figure 7.9b shows the final

[7]https://www.fablabs.io/labs/fablabnepal

assembly of *Smart Motors* built by Karkhana Samuha, Nepal.



(a) Final PCB design with the soldered components.

(b) Fully assembled *Smart Motors*.

Figure 7.9: Final PCB design and assembly of *Smart Motors*.

7.3 Future Work

As demonstrated through the descriptions of various prototypes in Chapter 3 and prototypes built in Brazil and Nepal using locally available materials in this chapter, the idea of *Smart Motors* can be implemented on different hardware platforms. We have tested this on several other platforms like LEGO® SPIKE™, micro:bits, Seeeduino Xiao, and documented the instructions in a publicly available website[8] as shown in Figure 7.10. In addition to the instructions on building *Smart Motors*, we have included several resources for teachers to use on the website in placemat format [91]. The future work includes testing more platforms, updating the information on the website, and adding more teacher instructions.

[8]http://smartmotors.ai

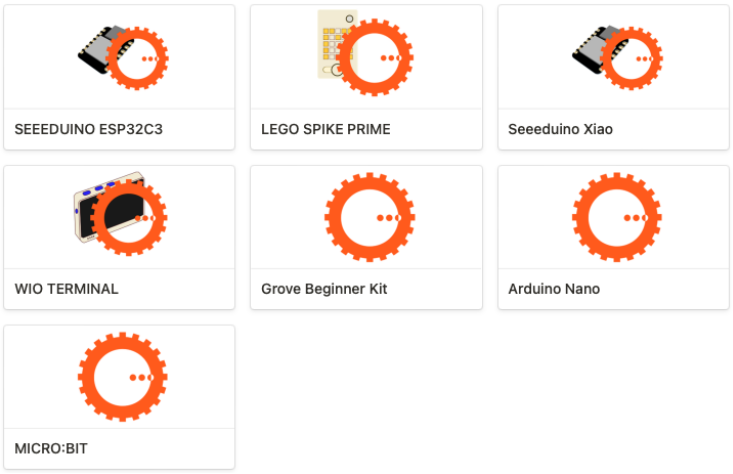


Figure 7.10: List of platforms used to build *Smart Motors* with publicly available instructions.

We have also created a web application[9] for teachers and students with access to computers and the internet to use the computer screen for improved user experience and to gain more insights into the data. A separate code enabling communication between the *Smart Motor* and computer must be installed to utilize the website and its features. The future work includes adding more features to the website and adding the ability to seamlessly install the standalone version and web version of code on the *Smart Motors* from the website.

We will continue improving the *Smart Motors* V3 to include more onboard sensors to support innovative and creative project ideas. The current design allows for expanding the supported sensors to include I2C sensors. So, we will work on developing prototypes and testing them. There are many possibilities for additional sensors, including cameras or GPS sensors.

We have several ongoing projects for training teachers to teach machine learning (ML) and artificial intelligence (AI) using *Smart Motors*. We will continue

[9]https://smart-motors.web.app

supporting the current teachers and expanding our network to reach more teachers. We will continue working with our partners to support them in their endeavors to bring educational robotics into more classrooms in more playful ways and seek more partners to expand our work.

7.4 Conclusion

In this dissertation, I presented a unique approach to achieving desired outputs from robots by training instead of programming them, called *Smart Motors*, to address the issue of accessibility in educational robotics. Through the engineering design process, we developed *Smart Motors* kit under $30 that can be used in low-resource classrooms without computers to teach STEM using a playful approach. In this dissertation, I described our significant design decisions when developing the prototypes. I presented the findings from the usability test with the final version of *Smart Motors* that the participants from the 7-15 year age group were able to discover the *playing* and *training* features with various levels of support. The tests also revealed that users could successfully implement *Smart Motors* in various projects quickly. Using the case studies approach, I described in detail how *Smart Motors* can be integrated into STEM classrooms with students from various age groups to teach various topics, including engineering design, arts, science, storytelling, and game design. I used the results to discuss what results emerge through those integrations. Analyzing the characteristics of experience with *Smart Motors* in detail, I argued how playful activities designed with *Smart Motors* can enhance the playful learning experience of participants. Finally, I presented the collaborative work with our partners in Brazil and Nepal in developing and implementing local versions of *Smart Motors* and the work we will continue doing to make educational robotics more accessible and impactful worldwide.

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Appendices

Appendix A

Breakdown of Costs for V3

Table A.1: Detailed cost breakdown for V2.2 version of *Smart Motors* : *Smart Motors Module*

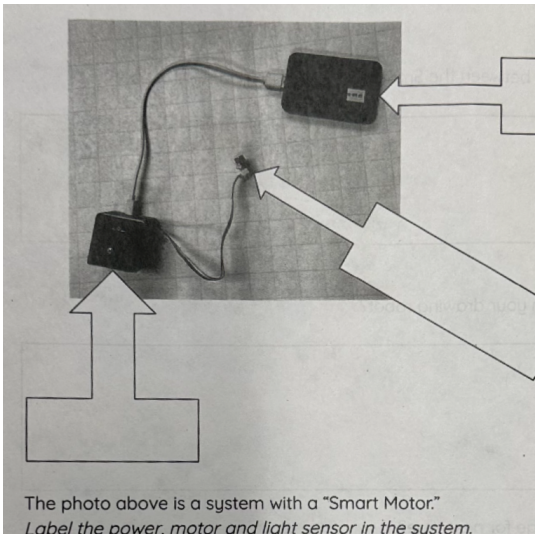
SN	Components	Parts	QTY	Unit Cost (2022)	Unit Cost (2024)	Cost (2022)	Cost (2024)
1	Smart Motor PCB	CUSTOM	1	$0.50	$0.50	$0.50	$0.50
2	Microcontroller	ESP8266 Mini D1	1	$3.08	$2.94	$3.08	$2.94
3	M5 Stack Servo Motor	SKU: A076-B	1	$3.98	$6.48	$3.98	$6.48
4	3x1 male connector	Male Header Pins (2.54 mm)	1	$0.04	$0.13	$0.04	$0.13
5	Training Module Port	1445022-4	1	$0.34	$0.37	$0.34	$0.37
6	Grove Sensor Port	110990030	1	$0.17	$1.70	$0.17	$1.70
7	Custom Button PCB	CUSTOM	1	$0.50	$0.50	$0.50	$0.50
8	Latching Button	MPBSS-6P-7X7-20	1	$0.35	$0.53	$0.35	$0.53
9	90 degree header pins	B08WYC3S6Y	1	$0.05	$0.06	$0.05	$0.06
10	Battery Port	S2B-PH-K-S(LF)(SN)	1	$0.15	$0.12	$0.15	$0.12
11	LiPo Battery	Adafruit 1317	1	$5.95	$5.95	$5.95	$5.95
12	SMD charging chip	MCP73831T-2ACI	1	$0.10	$0.76	$0.10	$0.76
13	SMD voltage reg. chip	AP7361-33ER-13	1	$0.35	$0.42	$0.35	$0.42
14	SMD capacitor	GRT21BC71H475KE13L	4	$0.19	$0.47	$0.76	$1.88
15	SMD 2k resistor	RC0805FR-072KL	1	$0.02	$0.10	$0.02	$0.10
16	SMD 470 resistor	CRG0805 5% 470R	1	$0.01	$0.10	$0.01	$0.10
17	SMD 1k resistor	CRG0805 5% 1K0	1	$0.01	$0.10	$0.01	$0.10
18	SMD LED	SML-H12P8TT86C	1	$0.13	$0.45	$0.13	$0.45
19	3D print	CUSTOM	1	$0.76	$0.76	$0.76	$0.76
	Total					$17.25	$23.34

Table A.2: Detailed cost breakdown for V2.2 version of *Smart Motors* : *Training Module*

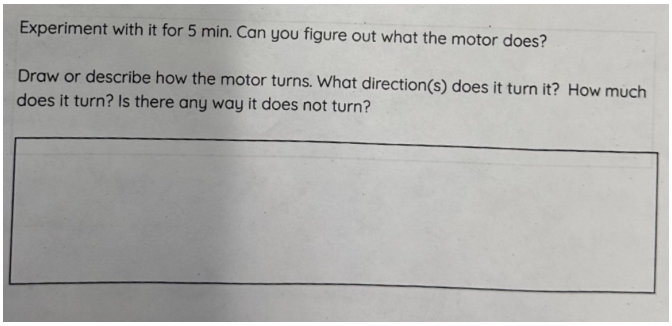
SN	Component	Part	Quantity	Unit Cost (2022)	Unit Cost (2024)	Cost (2022)	Cost (2024)
1	*Training Module* PCB	CUSTOM	1	$0.50	$0.50	$0.50	$0.50
2	Potentiometer	PTV09A-4225F-B103	1	$0.63	$0.71	$0.63	$0.71
3	Connector Female	2-1445055-4	1	$0.34	$1.25	$0.34	$1.25
4	Connector Male	1445022-4	2	$0.34	$0.37	$0.68	$0.74
5	Crimp	1-794610-1	8	$0.12	$0.16	$0.96	$1.28
6	1x20 Headers	Male Header Pins (2.54 mm)	2	$0.25	$0.25	$0.50	$0.50
7	Training Module	Wio Terminal	1	$36.90	$29.00	$36.90	$29.00
8	Battery pack	Wio Battery pack	1	$25.2	$25.20	$25.20	$25.20
	Training Module Total					$65.71	$59.18

Appendix B

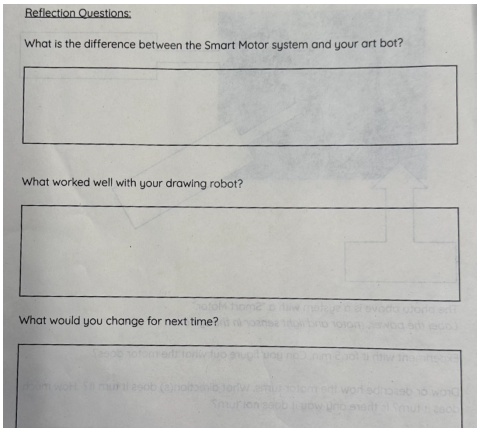
Activity Sheets for Proof-of-Concept Study 2



(a) Labeling the *Smart Motor Module* parts.

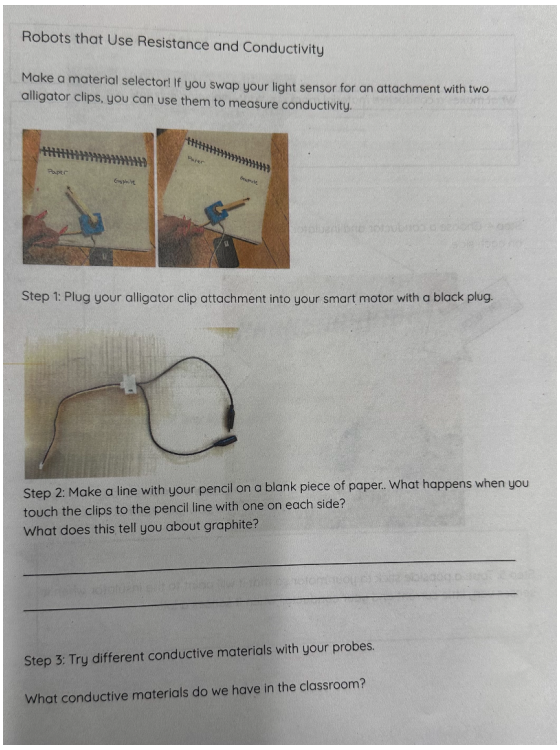


(b) Prompt to observe the *Smart Motor* and its functions.



(c) Reflection questions for the end of the activity.

Figure B.1: Activity sheet instructions for lesson 1 in study 2 discussed in Chapter 4.



Robots that Use Resistance and Conductivity

Make a material selector! If you swap your light sensor for an attachment with two alligator clips, you can use them to measure conductivity.

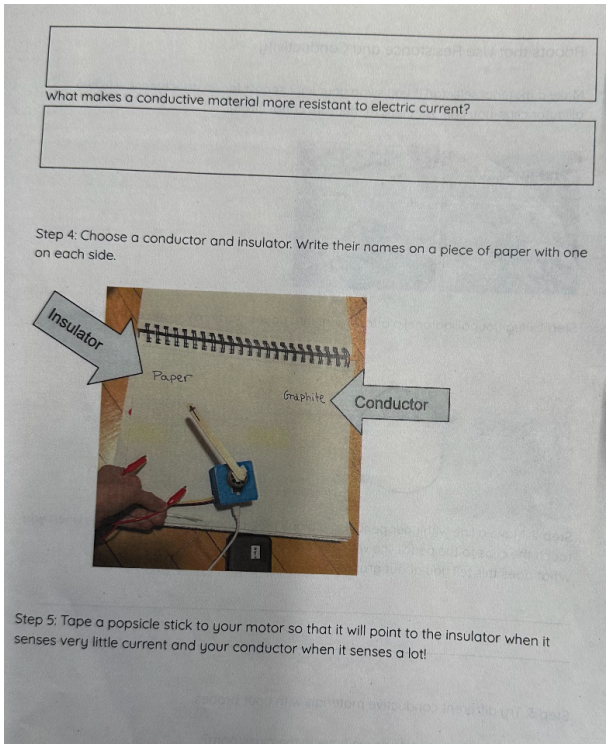
Step 1: Plug your alligator clip attachment into your smart motor with a black plug.

Step 2: Make a line with your pencil on a blank piece of paper. What happens when you touch the clips to the pencil line with one on each side?
What does this tell you about graphite?

Step 3: Try different conductive materials with your probes.

What conductive materials do we have in the classroom?

(a) Page 1.



(b) Page 2.

Figure B.2: Instructions for lesson 2 in study 2 discussed in Chapter 4.

Appendix C

Questionnaires and Activity Sheets for *Smart Motors* V3 Usability Test

Table C.1: Pre-test questionnaire for *Smart Motors* usability test

No	Questions	Response
1	Name	.....
2	Age	.....
3	Have you played with robots before?	Yes No
4	If yes, which ones?	.....
5	Have you played with LEGO before?	Yes No
6	Have you done any programming? Eg. Scratch, Python	Yes No
7	If yes, which ones?	.....
8	Do you like playing with robots?	Yes No
9	Why?	.....
10	How comfortable are you in testing new robotics toys?	1. Very comfortable 2. Somewhat Comfortable 3. Neither comfortable nor uncomfortable 4. Somewhat uncomfortable 5. Very uncomfortable

Table C.2: Post-test questionnaire for *Smart Motors* usability test

1	Did you like *Smart Motors*?									
	No 1	2	3	4	5	6	7	8	9	10 Yes
2	Would you use a *Smart Motor* again?									
	No 1	2	3	4	5	6	7	8	9	10 Yes
3	Will you tell your friends about *Smart Motors*?									
	No 1	2	3	4	5	6	7	8	9	10 Yes

Table C.3: Prompt and questions for Activity 1 of usability test

ACTIVITY 1 (5 minutes)	
Prompts	
1	Connect the LEGO arm to the Smart Motor
2	Observe what happens when you cover and uncover the sensor with your hand.
Questions	
1	Describe or sketch the behavior of the motor. Explain what is happening and why you think it is happening.

Table C.4: Prompt and questions for Activity 2 of usability test

ACTIVITY 2 (5 minutes)	
Prompts	
1	Use the Smart Motor and teach it to do a waving motion.
Questions	
1	Why do you think the motor behaves this way? Describe or sketch the behavior of the motor.
2	Rate the difficulty level of this task. Circle your choice.
	i. Very challenging
	ii. Somewhat challenging
	iii. Neutral
	iv. Somewhat easy
	v. Very easy
3	What was challenging about the task? Describe

Table C.5: Prompt and questions for Activity 3 of usability test

ACTIVITY 3 (5 minutes)	
Prompt	
1	Use the same motor and make the motor wave differently.
Questions	
1	What did you change? Describe or sketch.
2	Did it work the way you expected?
	a. Yes,
	b. No
	c. Not exactly (explain) . . . . .
3	Rate the difficulty level of this task. Circle your choice.
	i. Very challenging
	ii.
	iii. Neutral
	iv. Somewhat easy
	v. Very easy
4	What was challenging about the task? Describe

Table C.6: Prompt and questions for Activity 4 of usability test

ACTIVITY 4 (20 minutes)	
PART 1 (4 minutes)	
Prompt	
1	Think of an activity you did this summer. Think how you would represent that activity using a Smart Motor and the provided LEGO pieces.
2	Draw a sketch of the activity.
3	Sketch/Description of how you want to build the activity with Smart Motors
PART 2 (15 minutes)	
Prompt	
1	a. Represent the activity you thought about using Smart Motors. You have 15 minutes to complete.
PART 3 (1 minute)	
1	When you are finished, give a verbal description of the activity you built.
Questions	
1	How well do you think you were able to represent the activity using Smart Motors? (Likert scale)
	(Very well) 1 2 3 4 5 (Very poorly)
2	What would you do differently if you were to do it again?

Appendix D

Results from Usability Tests

Table D.1: Pre-test questionnaire responses

No	Age	A	Which?	B	C	Which?	D	Why?	E
1	12	Y	LEGO SPIKE Prime	Y	Y	Scratch	Y	They show me that technology can do amazing things	5
2	9	Y		Y	Y		Y	Because it can be cool to study how they work	5
3	8	Y		Y	Y		Y	They are cool and I don't get to play with it very much	4
4	11	Y	Don't remember	Y	Y	Scratch	Y	It is fun testing the bots and if they are successful I can brag about it.	5
5	8	Y	LEGO SPIKE Prime	Y	Y	Scratch, Python	Y		4
6	7	N		Y	Y	Scratch	Y	because they are fun	5

Table D.1 Continued:

7	7	Y	LEGO SPIKE Prime	Y	Y		Y	It is fun.	5
8	9	Y	Sphero	Y	Y		Y	They are fun to use.	5
9	12	N		Y	N		Y	I feel like it could be a fun experience.	5
10	14	Y		Y	Y	Scratch	Y	I find robots interesting.	4
11	9	Y	EV3	Y	Y		Y	It's fun to play with robotics.	5
12	13	Y	A lot, Little Bit is one example	Y	Y	Scratch	Y	I think its fun to see how they can help us	5
13	14	N		Y	N		N	Doesn't really pique my interest	3
14	10	Y	toys at home	Y	Y	Scratch + toys	Y	Because I like to code/make thing work	5

Table D.1 Continued:

15	12	Y	LEGO SPIKE Prime	Y	Y	Python and Java	Y	It's very fun to do	5
16	8	Y	Technic	Y	Y	Scratch	Y	because they are cool	5
17	14	Y	LEGO Mindstorms	Y	Y	Scratch	Y	It is fun to see them do things I can't	5
18	10	N		Y	Y	Scratch	Y	They are fun to use.	5
19	8	N		Y	N		Y		5
20	15	Y	LEGO Mindstorms	Y	Y	Scratch	Y	Its fun	5
21	13	Y		Y	Y		Y	I like being able to code them to do things	5
22	7	Y		Y	N		Y	They are fun to use.	4

Table D.2: Summary of responses from pre-test survey

Age	Freq.	A		B		C		D	
		Yes	No	Yes	No	Yes	No	Yes	No
7	3	2	1	3	0	2	1	3	0
8	4	3	1	4	0	3	1	4	0
9	3	3	0	3	0	3	0	3	0
10	2	1	1	2	0	2	0	2	0
11	1	1	0	1	0	1	0	1	0
12	3	2	1	3	0	2	1	3	0
13	2	2	0	2	0	2	0	2	0
14	3	2	1	3	0	2	1	2	1
15	1	1	0	1	0	1	0	1	0
Total	22	17	5	22	0	18	4	21	1

Index for Tables D.1 and D.2:

A : Have you played with robots before?

B : Have you played with LEGO before?

C : Have you done any programming?

D : Do you like playing with robots?

E : How comfortable are you in testing new robotics toys?

1. Very comfortable
2. Somewhat Comfortable
3. Neither comfortable nor uncomfortable
4. Somewhat uncomfortable
5. Very uncomfortable

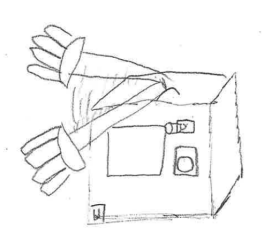
Y : Yes N : No

Table D.3: Observation after playing with pre-trained *Smart Motor*

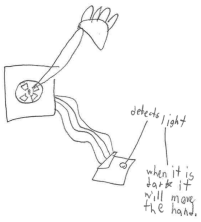
No	Age	Activity 1 observation
1	12	The motor is making the hand move due to the sensor being blocked.
2	9	The motor is very sensitive. And that when you twist the knob it twists one way.
3	8	When I covered the light sensor, it went left, and when I didn't cover the sensor, it went right.
4	11	Sensor detects light. When it is dark it will move the hand.
5	8	When the hand covers the sensor, there is no light detected, and it moves.
6	7	when there is no light, it moves to the left, and when there is light, it moves to the right.
7	7	I think there is a little sensor here, and if you touch it, it connects to this thing, and it starts moving. The line goes to the right and back on the screen.
8	9	When it isn't being covered it is pointing towards this way, when its covered the motor moves to the side. And on the screen, when it's not being covered, the dot on the screen moves to the top.
9	12	The arm of the motor is moving with the wheel as I hold the sensor. I think this is happening because the sensor can detect the motions of my hand and make the wheel move.
10	14	The motor is moving the hand in a waving motion. When I touch the sensor, it tells the motor to move.
11	9	When the motor sees my hand it moves. The light sensor saw some change and sent electrical force to the motor to make it move.
12	13	When I cover the sensor, the arm moves from dot to dot. I think the dots represent points that the motor can move to, and it is reading different ones when the sensor is covered or uncovered.
13	14	The behavior of the motor is that it is snapping to 3 predetermined positions depending on how much light it is receiving.
14	10	Basically, I can put points, and I can spin the motor with a knob. I can delete and add different things. I can go up and press play. And when the motion detector senses movement, it will go to different places on the screen where you have dots and moves.

Table D.3 Continued:

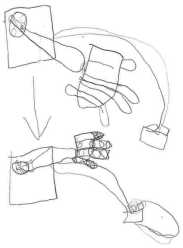
15	12	It sends a signal to the motor to move.
16	8	The hand moved right when I covered the sensor
17	14	When I cover the light sensor or press the green button, the arm is jumping from the left to the right.
18	10	The motor moves. The motor moves the arm.
19	8	I see that the motor moves when I show the light sensor and when I cover it doesn't move.
20	15	It moves to the right when my hand covers the sensor
21	13	the arm attached change position
22	7	It moves from here to the other side when I hold cover this.



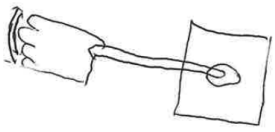
(a) Participant 1



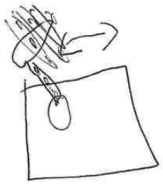
(b) Participant 4



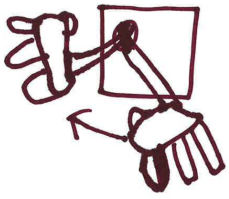
(c) Participant 8



(d) Participant 11

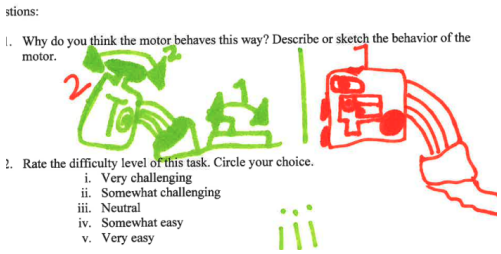


(e) Participant 18



(f) Participant 22

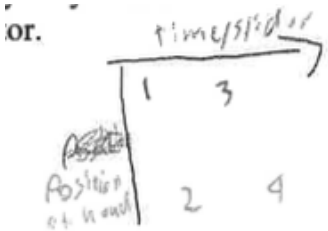
Figure D.1: Sketches made by participants to describe the behavior of pre-trained *Smart Motor*.



(a) Participant 5



(b) Participant 15



(c) Participant 17

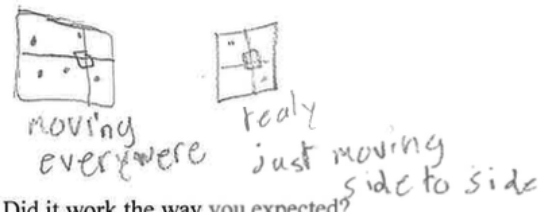
Figure D.2: Sketches made by participants to describe the behavior of *Smart Motor*.

Table D.4: Observation after training the motor *Smart Motor*

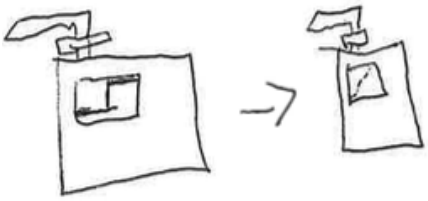
No	Age	Activity 2 observation
1	12	I think the motor behaves likes this because two points were marked as data, and when I hit play, the robot moved according to the data on the sensor.
2	9	I think the motor behaves this way because for it to work it needs enough programming.
3	8	From the boxes
4	11	It stores the data of the little points on the plus option. Then carries it to the play option where it uses that to create specific movement.
5	8	*sketch shows they moved sensor, moved motor and trained*
6	7	Basically I made dots, I moved things to go to the dots and it moves. I created the dots by adding icon, moved the potentiometer, and pressed the green button.
7	7	I programmed it and I put the dots. I used the sensor to left and right, this (pot) to move the motor.

Table D.4 Continued:

8	9	When I move it over here it is pausing, when I move it all the way over there it is on. So it is acting like an ON and OFF switch.
9	12	The slider acts like a movement for the plotted dots making it move.
10	14	I think the dots when you put on screen is telling it where to move from one dot to the other.
11	9	
12	13	I placed the points and it was following my institutions
13	14	I think the motor behaves this way due ot it snapping to the nearest position that a vertical touches.
14	10	I added them in an arch kind of way, so it moved the thing back and forth. Cuz when I do this it's adding the motion to go to each dot. So when it went back and forth it looks like a waving pattern. And because I added the dots it knew, that was the coding the part, and to make it work I moved the sensor.
15	12	The points are the spaces for time and place.
16	8	I made the dots in the same place as the 1st one.
17	14	It is jumping between the points I gave it.
18	10	I am programming it so when I slide it it moves.
19	8	I think that because I waved I teached it how to wave
20	15	It goes to one point then the other on the screen, these are points set for it to go to when you use the switch.
21	13	I placed different points on a verticle line and pressed the play button.
22	7	I went to the plus, then I moved the sensor to the other side, made it go down, and pressed the big button, go to play. And it started to go.



(a) Participant 2



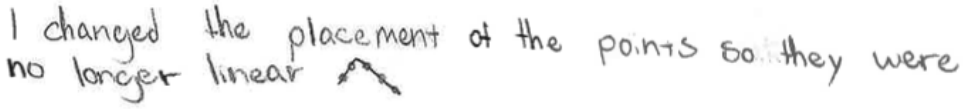
(b) Participant 18



(c) Participant 15



(d) Participant 16



(e) Participant 21

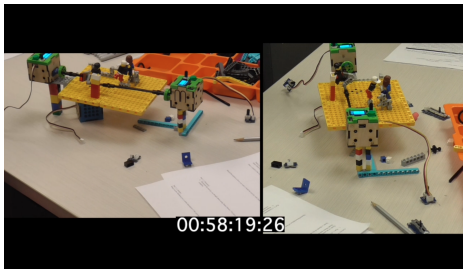
Figure D.3: Sketches made by participants to describe how they retrained their *Smart Motor*.

Table D.5: Participants' response to what they did to retrain the *Smart Motor*

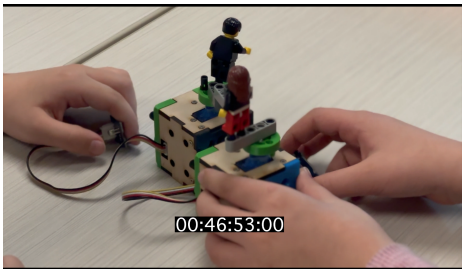
No	Age	Activity 1 observation
1	12	I put the data points on two different lines, and changed the sensor I used , which made it wave a bit bigger.
2	9	
3	8	I moved the boxes further than the last time.
4	11	I made it shudder a bit and move around in more ways so it danced a bit.
5	8	I just deleted a dot which was over there.
6	7	I changed the dots.
7	7	I changed the arm's direction of movement.
8	9	Instead of starting from one corner I made it start the other corner.
9	12	The placement of the dots.
10	14	I made it instead of going diagnoally one way I made it go the otherway. And I also made it stop in the middle.
12	13	I changed the control so that when its by the wires it is towards me and when its away from the wires it is away from me.
13	14	I changed how much the angle the arm moves by changing the y-axis difference was.
14	10	I added more dots up and around it took longer going back and forth. So just doing one wave I had to do back and forth with the controller. So I don't need to go back and forth as much now.
15	12	
16	8	I added more dots.
17	14	I made it so it moves farther each time it moves.
18	10	
19	8	I started moving faster with more force and is almost going all the way around the smart motor
20	15	I changed the position of the dots
21	13	I changed the placement of the points so they were no longer linear
22	7	I put another dot in the middle.



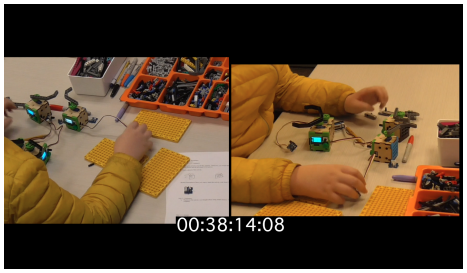
(a) Participant 1



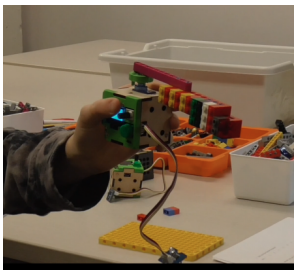
(b) Participant 2



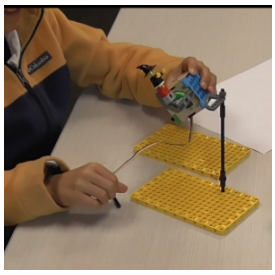
(c) Participant 3



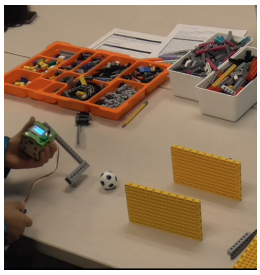
(d) Participant 4



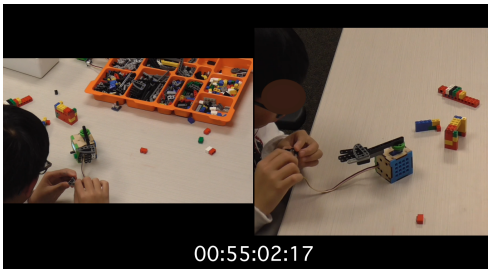
(e) Participant 5



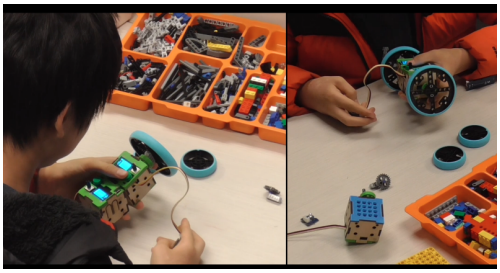
(f) Participant 6



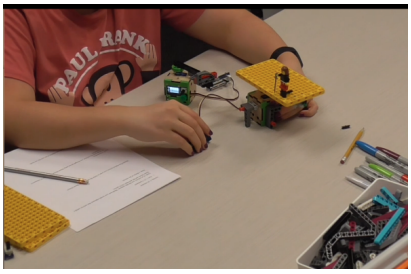
(g) Participant 7



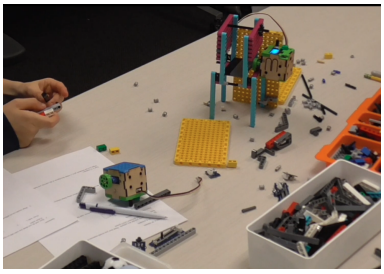
(h) Participant 8



(i) Participant 9

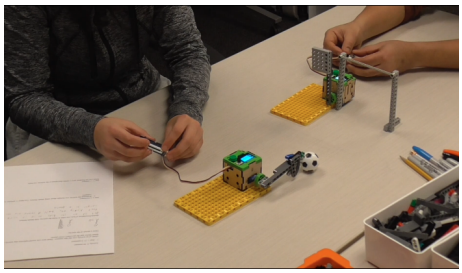


(j) Participant 10

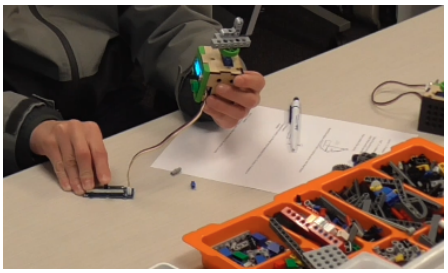


(k) Participant 11

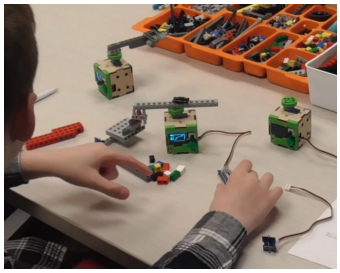
Figure D.4: Participants working on their build for Activity 4 - part 1.



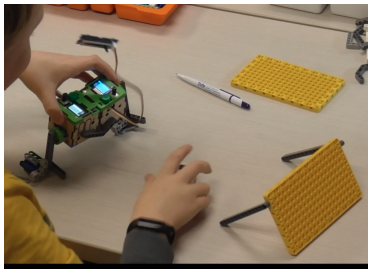
(a) Participant 12



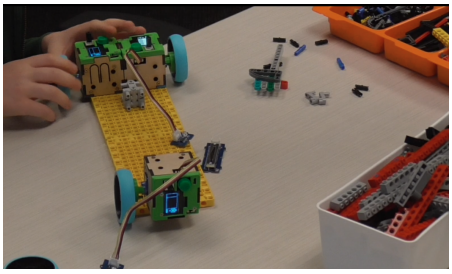
(b) Participant 13



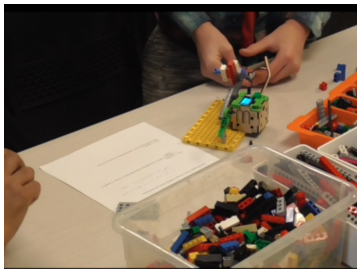
(c) Participant 14



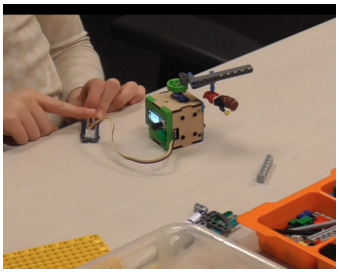
(d) Participant 15



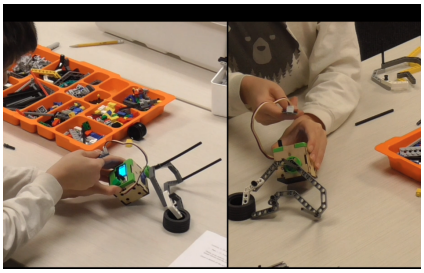
(e) Participant 16



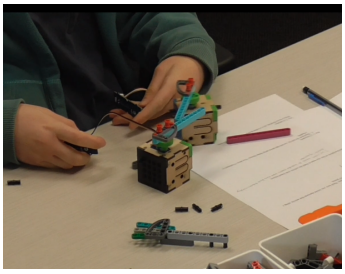
(f) Participant 17



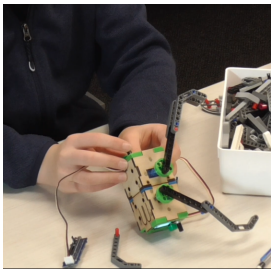
(g) Participant 18



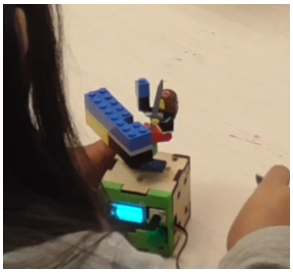
(h) Participant 19



(i) Participant 20



(j) Participant 21



(k) Participant 22

Figure D.5: Participants working on their build for Activity 4 - part 2.

Table D.6: Participants' description of their projects in Activity 4, their rating of how well were they able to represent using the activity using *Smart Motors* with 1 being Very Well and 5 being Very Poorly and things they would improve.

No	Description of their project	Rating (1-5)	Description of what they would change
1	I was trying to make a grabber arm that would trab anything when I tell it to.	3.5	I would have used bit more motors, and bit more LEGO pieces that you wouldn't normally find. And I would figure out a way to get the motors to separate and comeback to make the grabber arm fully functional.
2	Basicaly, its like an obstacle course. The axle from one is connected to the smaller piece on the other.	2.5	make it stabler.
3	I would move the motor to dodge the snow ball.	3	making the arms for the snowball a little longer so its easy to hit or dodge. For Smart Motors maybe make it going different way, because I wanted it to hit this way I could have made it go this way.
4	So thi is a swimatron 3000. it can move its legs, and its arms. It has to be operated by two people with sliders so you can grab yourself a litle buddy or you will be sad.	3	Combine all of the pieces so it looks more human.
5	I am making a little thing that you would put into a whole bunch of vegetables and you make salsa.	1	Use different sensors.

Table D.6 Continued:

6	I made a guy dunking a ball. You could use it go left and right, up and down.	1	I would reprogamm it.. Right now it is going half way. I can control it, it would go up and down now stop halfway.
7	I built like a soccer guy that kicks the ball.	1	I would make a goalie. It will take five hours.
8	I built hockey player that scores the goal.	2	Code it first, and maybe look at these (goal post) more stable and to represent something like a goalie.
9	a moving robot thing that cannot turn.	2	maybe change the motor layout.
10	I played a game called Croquet. It is a yard game, where you hit the ball with a mallet through hoops. It is supporsied to hit the ball into it	3	probably make this work better. Try and find to add more things.
11	I made a LEGO claw machine.	2	I cover it up and not make it look like cheese box
12	I made a soccer player and a goalie and it can kick a ball into the net. It is a two player game. I used a pot and slider	2	I would change the kicker to a light sensor, and the goalie to a slider. I would also make a better goal.
13	I made a sail rotating with the direction of the wind. I made more points to make it more linear with the the slider.	2	Make the representation of sail look better.

Table D.6 Continued:

14	At first I tried to make it push in and out. But I thought it would be more effective if I scooped it. You can also think of this as an art if you get it to spill on canvas. I had points that can connects that can connect freely even without the motor. and so when the motor works it can almost get a sense of its own. when the motor is involved it spins the whole thing.	1	I probably could have made it so that it could control itself. Made it a bit more compact and used a little pieces.
15	It is a soccer person, it is a lefty and can do back heel kick. I changed the hand into a foot. And it kicks the ball and is pretty good at it. I used slider because this is easier and I can set the position better. The light sensor is sensitive.	2	Probably make the feet go towards the backwards, and add some hands and a goal post.
16	So I made a scooter and I programmed only these two. It looks like a scooter.	2	Probably instead of using Smart Motors for the wheels I would use them for turning for the handle bar. So they could move and I could turn it.
17	So it's a plane flying from my house to a palm tree. When I cover the sensor, it goes from one place to another, and I took a bunch of different points. I used a light sensor because this would be much more smooth.	1	I would build the house differently.

Table D.6 Continued:

18	So this is me turning the corner. Here I am swimming during our recent vacation.	1	Make it sturdy so I do not crash or fall.
19	I am building a hand, and I am trying to use the motor to close the gap so I can pick things up.	3	try to make new design, ask my brother, show him my initial designs
20	I built sabers out of LEGO and added multiple different dots, so it can do to different directions and I did the same with the other. The more dots I added the more areas I could move to.	1	I could make swords and have the motors move them back and forth as if they were hitting each other.
21	Built a claw that can grab things.	3	probably change the placement of the claws.
22	I made me cut my birthday cake. The Smart Motor is showing everyone that I cut a piece of cake.	1	I wouldn't make it different.

Table D.7: Responses to the post-test questionnaire of the usability test

No	Age	Question 1	Question 2	Question 3
1	12	8	8	10
2	9	9	10	7
3	8	9.5	10	10
4	11	7	9	8
5	8	10	10	8.5
6	7	10	10	10
7	7	10	10	5
8	9	10	10	6
9	12	8	8	7
10	14	8	7	9
11	9	9	10	10
12	13	8	9	7
13	14	8	8	7
14	10	9	10	8.5
15	12	9	10	8
16	8	10	10	10
17	14	10	10	8
18	10	10	10	10
19	8	10	10	10
20	15	10	10	10
21	13	8	9	10
22	7	10	10	10

Index for Table D.7
Question 1 : Did you like *Smart Motors*?
Question 2 : Would you use a *Smart Motor* again?
Question 3 : Will you tell your friends about *Smart Motors*?

Appendix E

Results from Playful Learning Experience Tests

Table E.1: Coding of Tim's playful learning experience

Joyful		Actively Engaging		Iterative		Meaningful		Socially Interactive	
E	Opens the kit to take a look at the pieces	E	Checks the pieces	N	Haven't started	N	haven't started	N	Haven't started
E	takes pieces and starts building	E	checks the materials and explores	E	tries a build.	E	asks how many fingers does a hand have	E	talks about LEGO pieces
E	caught up in building	O	shows no interest to stop	O	identifies his design takes too many pieces	O	realizes that making good looking is not the goal	O	shares his pieces
E	starts playing with SM	E	explores how the arm would work	E	starts exploring SM	O	realizes his build waves differently that he wants	O	acknowledges his teammates creation
O	continues despite frustration	O	coninues despite distractions	R	starts making changes how the arm is attached.	O	tells he wants a particular way of waving	O	shares ideas with Keshav
O	enjoying despite not the result he wants	O	intently tests the sensor and traisn the motor	O	Wants to change the waving pattern	O	shares he wants his arm to move fast	O	shares his build and his intentions
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.1 Continued:

O	caught up in retraining	R	focussed on retraining to make it work	R	starts retraining it with more data points	R	he is training so it waves fast	E	notices Keshav's design and compliments
E	picks up new SM2	E	Intestered in the new tool	E	Tries out SM2	R	plays with SMs and realizes what they can do with it.	O	shares LEGO pegs with Jason
E	Curious how he would use the arm on SM2	E	attaches the arm to the SM2	E	Tests the arm on SM2	O	Developing understanding of how it works	O	Lets Jason show him his creation and acknowledge
O	caught up in rebulding from scratch	E	tries out new design	R	deliberate about how he wants the arm to move	O	He is trying to build it to wave horizontally	N	tries things alone
O	Caught up in mounting the SM , poking holes with axle	R	makes the hole work on the SM by poking with axle	O	Moves the SM around so another beam can slide under the wheel	O	shares how he wants the arm to move	E	talks with Jason about broken LEGO pieces
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.1 Continued:

O	attaches the arm to the sliding beam	R	Connects the arm to the LEGO beam, he is making the horizontal wave	E	attaches the arm to the beam	O	attaches arm so it moves the way he wants	O	Shares pieces with Jason
O	carries on despite pressure.	R	Focussed on securing the motor the motor despite the 2 minutes remaining call	R	knows exactly how to make it secure. adds beams	R	noticed the arm flailing , so he is securing it.	N	totally focussed on his own work
O	Carries on despite last minute issues.	R	Noticed the problem, and immediately jumped to solve it.	O	realizes the arm is weak and tweaks the build to make it secure. and retrains	R	Realized the arm is weak and not moving properly.	E	briefly looks at Jason's build. and compliments
O	Caught up in the activity even in the dying moments	R	maintains focus to finish the build	E	makes final adjustments and gets ready to share	R	Keeps training to get to work despite calls to stop working	N	focussed on completing his build

Table E.2: Coding of Jason's playful learning experience

Joyful		Actively Engaging		Iterative		Meaningful		Socially Interactive	
N		N		N		N		N	
E	Interested in the experience. thinks outside the box	E	Checks the pieces	E	starts connecting pieces.	O	tells what he is going to do	O	shares idea with Keshav and Tim on what it could look like
E	Checks how the pieces attaches to the motor , tried moving potentiometer	E	checks the materials and sees how they work	E	testing out the pieces and SM	O	connects the beam to the wheel and starts moving it: the goal	R	Negotiates how the pieces should be divided.
E	Trains the SM	O	Very focussed on training the motor.	E	Looks for pieces.	O	developing an understanding of how SM works	R	Negotiates with Tim about lack of pieces
E	still trying to figure out the connections	E	Interested in right LEGO pieces to connect	O	knows that the current way of arm moving is not ideal	R	says that he wants the motor to not be "horrendous"	O	Let's Keshav know that all the motors just move in an unappealing way.
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.2 Continued:

O	Doesn't know how to make it curl, but still tries and explores	O	Tries to build the curling mechanism but can't find the right pieces	O	Takes things apart and builds an arm with beams	R	Has an idea of making the	O	Checks with Keshav if curling arm counts as waving
O	focussed on geting his idea built	O	focussed on the activity	E	Exploring how things work	O	He builds towards the curling hand	O	Double checks Keshav if curling the hands counts as waving
O	caught up in the activity, that will fulfil the goal	O	Focussed on completing the challenge, even with a simple build	R	Pivots to making a simple arm	O	While he has pivoted to a simple build, he is still goal oriented	N	Works alone
R	Has trained a motor, with a simple arm build. and happy that it works	R	invested in getting the arm waving with sensor. and happy that it works	E	uses his training knowledge to train.	R	the success with simple arm ensured he had something to show	O	Shows his arm waving to his teammates
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.2 Continued:

O	goes back to the curling motion. even if it is challenging	R	He seems invested in getting the curling to work	R	he is deliberate about this design change.	O	Does say it but going back to his original plan shows it is meanigful to him.	N	Works alone
O	appears to be caught up in his idea.	O	focussed on his build	O	changes the number of beams he was using, to make it simpler	O	he now has two beams that will be his arms that will curl in	O	Shares pieces with Tim
O	“its not going to work”, but conistently ties to make it work	R	not distracted by Keshav’s motor whirling nearby	O	realizes that something doesn’t work and adjusts	O	he has now mounted a plate to hold the arm.	O	Shares pieces with Team.
O	hurrying a little bit, but wants to complete the build	R	thoroughly engaged in his build	O	adjusts how the piece are connected, changs the axle	O	the actions are goal oriented	N	Works alone
R	smiles widely as the motor turns, and the arms curl	R	finally gets the build right, and gets the arm waving	E	checks how the speed changes the waving pattern	R	demonstrates how his vision came to fruition	O	shows his creation others not involved in creating
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.2 Continued:

E	strengthens the build and cleans the desk.	O	continues to secure	E	adds some pegs to make it secure	O	wants to make sure the build is strong for demo	N	not observed

Table E.3: Coding of Keshav's playful learning experience

Joyful		Actively Engaging		Iterative		Meaningful		Socially Interactive	
N	No opportunity to observe	N	No opportunity to observe	N	No opportunity to observe	N	No opportunity to observe	O	Moves closer to others and asks what they want to do.
E	Picks up LEGO pieces and explores	E	Picks random available pieces and stats exploring	E	Interacts with the exerience	E	just attending to the experience	O	Talks about inputs with Jason
E	Seems to be enjoying the build	O	focussed on the build	O	adjusts how the pieces are connected to make it look more like arm	E	at this point they are attending to experience	E	takes glances at what Tim and Jason are doing
O	hasn't done anything challenging, but seems to be enjoying	E	checks to see what he can do	E	repeats the action to try to connect the arm to motor	O	Shares how his hand will wave	O	Checks with teammates if his looks like a hand and shares how a hand should wave with Tim
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.3 Continued:

E	tries moving the arm with the pot to see how it moves.	O	focussed on making the arm wave	E	repeats the action with potentiometer	O	says his arm's jerkiness looks like robot waving	O	Requests for blue pins with his teammates
R	pretty satisfied with how his hand looked	O	focussed on improving his arm design.	E	Adds more beams to make the arm have more fingers	O	wants to make arm more arm like	O	asks Jason if it looks like it is handish.
R	trains the motor, and plays with it. seems content	E	Interesting in showing his arm to his teammates	E	redoes the training, makes the arm go left and right	O	trains the motor to achieve the goal of the exercise	O	Shows his build to everyone. displays for almost a minute
E	"is this all we need to do", shows curiousity	E	checks the SM2 motor.	E	explores the new motors.	O	tests the motors, and discovers that they are strong.	O	shares with the team his findings about the SM2
E	Explores the gears and how they turn	E	interested in gears	O	tries to make a different waving mechanism	O	testing out a different way to make the arm wave with beveled gears	N	No opportunity to observe
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.3 Continued:

O	struggles to get the gears attached but he persists	O	focussed on the activity. not distracted.	O	adjusts his approach by attaching another gear directly on the box	O	looks like his idea is to make the arm wave in a different plane that that of the motor.	N	No opportunity to observe
O	appears to be caught up in his explorations	N	No opportunity to observe	O	realized the gears are difficult to orient, and takes them apart	O	testing how the gears worked, and if it was possible to use them	O	Shares pieces with the teammates
P	goes back to the original design.	O	builds the arm , ready to show off	R	deliberate about the changes in his design, as he goes back to his original idea	P	looks like he is just doing because he has to demo it.	R	helps Jason figure out how to turn off his motor, by exiting the play mode
N	No opportunity to observe	P	he is distant from engagement from occassional display of his demo	N	No opportunity to observe	N	No opportunity to observe	O	shows off his build to anyone who is willing to see.
N	No opportunity to observe	N	No opportunity to observe	N	No opportunity to observe	N	No opportunity to observe	E	Watches Jason's arms curl, and enjoys it.
Index: N = No Observation P = Passive E = Exploring O = Owning R = Recognizing T = Transferring									

Table E.3 Continued:

N	No opportunity to observe	N	No opportunity to observe	N	No opportunity to observe	N	No opportunity to observe	E	Curiously checks if Tim was able to complete his build