Designing Child Robot Interaction for Facilitating Creative Learning

by

Safinah Arshad Ali

B.Des, Indian Institute of Technology
MHCI, Carnegie Mellon University

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of

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Author .... Signature redacted ....
Safinah Ali
Program in Media Arts and Sciences
August 9, 2019

Certified by .. Signature redacted ....
Cynthia Breazeal
Associate Professor of Media Arts and Sciences

Accepted by . Signature redacted ....
Tod Machover
Academic Head, Program in Media Arts and Sciences

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Children's creativity – the ability to come up with novel, surprising, and valuable ideas – has been known to contribute to their learning outcomes and personal growth. Standardized ways to measure creativity and divergent thinking reported that as children enter elementary school, their creativity slumps and thinking becomes more convergent, especially around the 4th grade. One cause for this is school curricula become more structured and lose the aspect of creative play. This is especially concerning for kids growing up in the era of Artificial Intelligence, where mechanical and repetitive jobs that require structured thinking move to machines. To be successful in this world of intelligent agents, we must empower children not only to understand how these intelligent agents work, but also to be able to think creatively about generating new artifacts in consort with such agents, which requires imaginative novel thought.

In this thesis, I explore whether a social robot's interaction with children can be an effective way to help children think more creatively. I suggest two ways in which robots used as pedagogical tools can help children think more creatively are: 1. through artificial *creativity demonstration*, such as showing the use of novel ideas, and 2. through offering *creativity scaffolding*, such as asking reflective questions, validating novel ideas, and engaging in creative conflict.

I designed four collaborative game-based activities that involve child-robot interaction and afford different forms of creative expression: 1. Droodle Game, which affords *verbal* creativity, 2. Magic Draw, which affords *figural* creativity, 3. WeDo Construction with Jibo, which affords construction creativity and 4. Escape Adventure, which affords divergent thinking and creative problem solving. I designed the behavior of the robot such that it either scaffolds the child for creative thinking, or the robot gives the appearance of creative thinking by artificially emulating human creativity. I evaluated the role of the social robot in influencing children's creativity by running comparative studies between children playing these creativity games while interacting with the robot with creativity-inducing behaviors (creative condition), and without creativity-inducing behaviors (non-creative condition). Children who interacted with the creative robot exhibited higher levels of creativity than children who interacted with a non-creative control robot. I conclude that children can model a social robotic peer's creative expression via social emulation. When scaffolded for creativity, children exhibited higher levels of creativity. This enabled me to develop a robot scaffolding paradigm which fosters creativity in young children.

This thesis contributes design guidelines for child-robot interactions which promote creative thinking, and provides evidence that these creativity inducing behaviors exhibited by social robots can foster creativity in young children.

Thesis advisor:
Cynthia Breazeal, Associate Professor of Media Arts and Sciences

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This thesis has been reviewed and approved by the following committee members

Cynthia Breazeal .... Signature redacted ....
Associate Professor
Program in Media Arts and Sciences, Massachusetts Institute of Technology

Rosalind Picard .... Signature redacted ....
Professor
Program in Media Arts and Sciences, Massachusetts Institute of Technology

Mitchel Resnick .... Signature redacted ....
Professor
Program in Media Arts and Sciences, Massachusetts Institute of Technology

Scot Osterweil ..... Signature redacted ....
Creative Director
Education Arcade, Massachusetts Institute of Technology

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Chapter 1 : Overview

1.1. Introduction

Creativity has been shown to facilitate problem solving, adaptability, self-expression and health. Creative thinking has both social and economic benefits [30]. Integrating creative skills into educational institutions' curricula provides increased learning benefits [42]. Economists suggest that most inventions today are a result of creative applications of existing knowledge and technology to new problems [16].

As we move from industrialized economies to creative economies, creativity is a crucial ability for the workplace. Standardized creativity measures have previously demonstrated that as children progress from kindergarten to elementary school, their creativity drops. As demonstrated by the Torrance Test of Creative Thinking (TTCT), there is a significant slump in grade four (ages 8-10) [52, 46]. It has been suggested that academic expectations from children and structured curricula that allow little space for play might lead to this fourth grade slump [51]. These structured school curricula lead to reduced divergent thinking and imagination, and we lose the benefits of the kindergarten style play-based learning strategies that promote creative thinking. This is especially a problem for a generation of kids growing up now, where applications of Artificial Intelligence (AI) become commonplace, and repetitive and mechanistic jobs shift from humans to computers. The technology that these children interact with changes rapidly. In this ever changing world, fostering creativity and imagination can help them succeed.

Children today interact with intelligent agents such as voice agents, recommendation systems, robots, etc. Children not only need to understand how these intelligent agents work, and also have the ability to think creatively and generate new ideas alongside these agents. From the literature of creativity we know that creativity can be learned and is influenced by a person's environment and social interactions [42].

Social robots have previously been used as pedagogical tools in classrooms and have been shown to be effective in enhancing cognitive and affective gains. Their ability to personalize learning and provide embodied and expressive interactions, which in turn lead to increased engagement, situate social robots well as learning tools in classrooms. Given how social interactions with others influence children's creativity, I am motivated to explore how we can use interactions with these social robots, that are already being used as pedagogical tools, as a means to foster creative thinking in children.

There are several frameworks of defining what qualifies as creativity and associated thinking behaviors such as generating novel ideas, divergent thinking, lateral thinking, and making unusual connections [6, 17, 30]. For the purpose of this thesis, I limit the definition of creativity to the ability to generate ideas with *fluency,* that have *novelty* and *value* [6]. *Fluency* refers to the ability of being able to generate several ideas. *Novelty* involves the ability to generate ideas that are different from your own previous ideas, and different from your group's ideas. The behaviors associated with novelty are the ability to make unusual connections, and recognize patterns. *Value* constitutes being able to generate ideas that add value to the problem being solved.

Creative ideas can be internally motivated, through personal interests, physical capabilities, or prior knowledge, or externally motivated, through social interactions with peers and tutors, or witnessing other creators [30]. Amabile & Gryskiewicz [2] and Witt & Beorkrem [57] identified the following "situational influences on creativity": freedom, autonomy, good role models and resources (including time), encouragement specifically for originality, freedom from criticism, and "norms in which innovation is prized and failure not fatal". It is, however, important to note here that factors such as competition and feedback can both stimulate and inhibit creativity depending on the person's perception [50]. In the context of learning, creative problem solving in classrooms is often scaffolded by extrinsic factors, such as social interactions with peers and teachers, the nature of collaboration, and the nature of the task itself [23]. Creativity is fostered when activities are presented in a permissive and gamelike fashion [53, 96]. Teachers and peers also act as potential models for creativity [42].

Researchers and educators have successfully deployed several technology enabled intelligent pedagogical tools in classrooms. Among these tools are artificial embodied agents such as social robots that have been used as effective pedagogical tools for young children leading to both cognitive and affective gains. Robots in education currently assume two roles. They act as social agents and take the role of a tutor or a peer [4], or serve as toolkits such as Lego Mindstorms or Popbots where children can construct robots to learn math, mechanics, and programming concepts [35]. Social robots offer an affordable and scalable way to offer personalized support to learners. Previous work has demonstrated the learning benefits of physically co-present robots versus video displayed agents [80]. As these robots become more accessible, and increasingly enter classroom and domestic environment, there arises a need to be mindful about designing the robots' social behaviors, such that they not only lead to cognitive gains in children, but also behavioral gains such as curiosity, mindset, persistence, engagement, and creativity. Among pedagogical tools, social robots have the unique ability to interact with children in a social emotional way because of their ability to perceive and express emotion. Since creativity is highly influenced by social interactions with others, I wanted to explore how we can make use of social robots to foster creative learning in children.

In the domain of creative learning, existing HRI approaches use robots as a *tool* for construction (such as Lego Mindstorms, programmable robots like Bots Alive, Cozmo, Pop bots, etc) [7, 8, 10, 31, 56]. However, using the social dynamic of tutor-learner interactions or peer-to-peer interactions with robots that facilitate creativity is a largely unexplored space, especially for children. In this work, I explore how the social verbal and non-verbal interactions of a robot can help children think more creatively. This is done in the context of game-based interactions that afford creativity as a central gameplay behavior.

Children are wired to learn with and from friendly others and socially emulate their behaviors [112]. Research in Human-Robot Interaction (HRI) has previously shown how robots demonstrating different learning behaviors such as curiosity, perseverance, growth mindset or engagement are socially modelled by children and influence their learning behaviors [18, 36]. In this work, I explore if interacting with social robots that exhibit artificial creative behaviors can help children think more creatively. I categorize the interaction pattern of robots exhibiting artificial creativity as *creativity demonstration* behavior. The robot is programmed to express atypical solutions, recognizing patterns, or exploring alternative methods to solve a problem.

Research in the field of HRI has shown that a robot's verbal and non-verbal behaviors such as question asking, positive reinforcement, challenging, and positive affect can help adults be engaged in a creative activity for longer times and come up with more creative ideas [28]. I term this interaction pattern as *creativity scaffolding* behavior, which constitutes the robot asking reflective questions, validating novel ideas, or engaging in creative conflicts.

1.1.1. Designing Child-Robot Interactions for Fostering Creativity

This work aims to evaluate how a robot's *creativity demonstration* is modeled by children and how a robot's *creativity scaffolding* behavior helps children be more creative. I first designed four game-based child-robot interactions, where children engaged in playful activities in the presence of the social robot Jibo, namely:

- Droodle Creativity Game where the child and the robot play a turn-taking Droodle game, which involves generating humorous and clever titles for abstract images.
- Magic Draw Game where the child and the robot collaboratively draw images on a tablet screen. The gameplay involves starting with a doodle and taking turns to finish a drawing of a common object.
- LEGO WeDo construction activity with Jibo, where the child and the robot collaboratively construct projects using the LEGO WeDo kit. The robot assumes the role of a mentor that scaffolds the child's learning.
- Escape the Room Adventure game with Jibo, where the child and the robot play a collaborative problem solving platform game involving a physics contraption simulated in a digital environment.

I outline the design of these game-based interactions, the design of the robot's *creativity demonstration* and *creativity scaffolding* interactions and the technical details of the system in **Chapter 3: Designing Child-Robot Interaction Design for Fostering Creativity**.

1.2. Research Questions

I further evaluated the role that social robots play in influencing children's creativity by running randomized controlled trials with a total of 214 children in the 6 - 10 year old age group. I ran three different comparative studies with children playing the Droodle Creativity Game, the Magic Draw Game, and the LEGO WeDo Construction Game with Jibo. In each activity, children were divided into two balanced groups (based on their age, gender, and creativity scores), one that interacted with the robot that exhibited creativity-inducing behavior and one that interacted with the robot that did not exhibit these behaviors. I ask the following research questions in order to identify the role of the social robot in promoting creativity in young children:

1.2.1. Do Children Socially Emulate a Social Robotic Peer's Creativity?

In the first two games, the social robot exhibited *creativity demonstration* behaviors, where it itself exhibited high levels of verbal and figural creativity. In the Droodle game, the creative robot exhibited verbal creativity through generating numerous and diverse Droodle ideas, and more creative titles. The robot also exhibited positive affect and positive feedback for children's ideas. The non-creative robot generated fewer Droodle ideas, less diverse ideas and less creative titles. The robot also maintained neutral affect. I observed that children who interacted with the creative robot exhibited significantly higher creativity in terms of *fluency*, *novelty* and *value* of ideas. In the Magic Draw game, the creative robot exhibited higher creativity by coming up with more creative drawings, as compared to the non-creative robot. The creative robot also articulated some of the creative process and creative reflections. I observed that children who interacted with the creative robot themselves made more creative drawings. Hence, I could conclude that children can successfully emulate a social robotic peer's verbal and figural creativity.

I outline the study design of these two *creativity demonstration* interactions in **Chapter4: Investigation I: Do Children Socially Emulate a Social Robotic Peer's Creativity?**

1.2.2. Can Robots Scaffold Children's Creative Learning?

In the third interaction, the social robot exhibited *creativity scaffolding* behaviors, where it assists the child in constructing WeDo models while encouraging them to think creatively. In this interaction, the robot is not autonomous and is controlled in a *Wizard of Oz* manner by human instructors. I co-designed a robot control interface with instructors to best enable them to provide scaffolding for creative thinking. Creativity exhibited in the task was measured in terms of the number of new ideas they came up with for the rover, the number of new functions they used for programming, and how uncommon their ideas were. Children who interacted with the robot exhibiting scaffolding behaviors exhibited significantly greater creative behaviors than children who interacted with the non-scaffolding robot that just provided construction instructions. I could conclude that the robotic interaction patterns did promote creativity in children, and hence lay out social interaction patterns for social robots that help foster creativity.

I also ran the same activity without the presence of a robot, where instructions were present on a tablet. These instructions were the same as the ones offered by the non-creative robot minus the embodiment. I observed no significant difference in the expressed creativity of the children while interacting with a tablet versus while interacting with a non-creative robot. Hence, it is not just the presence of an embodied agent, but also the design of the embodied agent's social behavior that influences children's creativity.

I outline the study design of the *creativity scaffolding* interaction in the **Chapter 5: Investigation II : Can Robots Scaffold Children's Creative Learning?**

In sum, this work aims to evaluate if a robotic peer's social behavior can help children think more creatively, and generate novel ideas. This is studied through 4 game-based child-robot interactions that afford creativity as a gameplay behavior. I hypothesize that children can be motivated to be more creative in these tasks by two kinds of behaviors that are exhibited by the robot:

- Robot *demonstrating* creative behavior
- Robot offering *creativity scaffolding*

I carry out randomized controlled trials to investigate the role that robots play in order to validate my hypotheses.

1.3. Thesis Contributions

This thesis explores how social robots' behavior can foster creativity in children. The proposed work is an attempt to evaluate whether children model creativity from a social robot and whether a social robot's *creativity scaffolding* motivates a child to be more creative. I propose a novel education technology system that integrates the fields of *social robotics, game design,* and *creative learning.* I design four game-based child-robot interaction systems that afford creativity as a gameplay behavior. I propose robot interaction patterns that can help enhance children's creative expression, through *creativity demonstration* and *creativity scaffolding.* The work contributes novel interaction patterns for artificial creativity, and evaluates how these robot interaction patterns help foster creative play in children. These interaction design patterns can potentially benefit both researchers studying social robots in education, and designers designing robotic literacy tools. Finally, I provide evidence how these robot interaction patterns can lead to creativity gains in children by conducting evaluation studies with children. This is the first such study aimed to evaluate the role of robots to facilitate creativity in participants of such a young age.

As we start to introduce robot based learning tools in classrooms, such technologies can help promote creative learning gains in addition to cognitive learning gains. This work also contributes tools that introduce Creative AI to children in a fun game-like manner and through an embodied social agent. Previous research in developmental psychology has discussed how creative application of existing knowledge and technology to new problems contributes to a creative workforce and helps drive innovation. The ability to think creatively could help children shape their future in this era of AI.

1.3.1. Designing Child-Robot Interactions to Foster Creativity

Creativity in a task is often influenced by external factors such as the person's surroundings, interaction with others, collaboration, affect, etc. One such factor is the nature of the task itself. In order to understand the role that social robots can play in fostering creativity in children, I designed four game-like child-robot interactions with the goal of fostering creative learning in children. These interactions afford different types of creativity, including *verbal creativity,* that is the ability to generate verbal artifacts such as stories, poetry and discourse, *figural creativity,* that is the ability to generate visual artifacts such as images, paintings and sculptures, *construction creativity,* that is the ability to out modular blocks (physical or digital) together to construct new artifacts, and *divergent thinking,* that is the ability to generate several atypical and unusual ideas.

The first interaction was the Droodle Creativity Game where the children and the robot play a turn-taking Droodle game, which involves generating humorous and clever titles for abstract images. The second interaction was the Magic Draw Game where the children and the robot collaboratively draw images on a tablet screen. The gameplay involves starting with a doodle taking turns to finish a drawing of a common object. The third interaction was the LEGO WeDo construction activity with Jibo, where the child and the robot collaboratively construct projects using the LEGO WeDo kit. The robot assumes the role of a mentor that scaffolds the child's learning. The fourth interaction was the Escape the room adventure game with Jibo, where the child and the robot play a collaborative problem solving platform game involving a physics contraption simulated in a digital environment.

The primary goal of designing these four interactions is to afford creativity as a gameplay behavior. I adopt design ideas from creativity measures (such as the Droodle Task measure [24], and the Figural TTCT measure [51], etc.), existing games that involve creative expression (such as Pictionary, The Incredible Machine [93], etc.) and existing pedagogical tools that foster creative learning (such as LEGO WeDo 2.0 kits, LEGO Mindstorms, etc.), for the design of the game itself. All the games involve interactions between the child, the robot and an Android tablet application. I iteratively designed these games through rounds of playtesting and gathering feedback from children and mentors. In each game, the robot assumes a different role, a peer or a tutor, and a different behavior, *creativity demonstration* or *creativity scaffolding* behavior. For designing the robot behaviors, I learn from the literature of creativity and creative learning about which behaviors of peers and tutors positively influence children's creativity. Further, for the *creativity scaffolding* interactions, I adopt a *learning from the wizard* approach, where the robot learns scaffolding behaviors from a human instructor's scaffolding behaviors. In this interaction, the robot is remote-controlled by a human instructor in a *Wizard of Oz* manner, using a dynamic scaffolding interface, that I developed iteratively while learning from human instructors and co-designing with them. I present the game design and robot interaction pattern design that each of these four systems. I also present the design of the instructor's control interface for the WeDo task. Further, I also present metrics of creativity measurements in each of these tasks.

These game-like interactions can be used by creative learning researchers, educators, and parents for providing fun activities for children that help them express themselves creatively. Further, they also serve as effective ways to measure children's creativity in a less task-like manner and can be used as assessment measures by creativity researchers. Most importantly, these games are fun activities for young children that enable them to generate art (in the form of discourse, drawings, physical models, or physics contraptions) in a safe environment.

1.3.2. Investigating the Role of Social Robots in Fostering Creativity in Children

I evaluated whether the proposed robot interaction patterns foster creativity in children by running randomized controlled trials with children. I evaluated the role of both *creativity demonstration* and *creativity scaffolding* on children's expressed creativity in the context of the child-robot games. I hypothesized that children that interacted with robots that demonstrate higher creativity and that scaffold the children's creative learning, will show higher levels of expressed creativity in the context of these game tasks.

In order to evaluate if children model a social robotic peer's creativity, I ran two studies, one where the robot expresses verbal creativity in the Droodle Creativity Game and, one where the robot exhibits figural creativity in Magic Draw game. In both user studies, I divided the participants into three balanced groups, 1. a creative robot group (R_C+) - where the robot was present as a collaborative player that demonstrated high creativity, 2. a non-creative robot group (R_C-) - where the robot was simply present as a player in the game but did not demonstrate high creativity, and 3. a tablet only group (T_C-), where participants performed the same activity but in the absence of the robot, and only with the tablet. I compared the creativity measures of the non-creative robot condition (R_C-) to the creative robot condition (R_C+), to evaluate how the robot's *demonstration* of creative behavior is modelled by the children. I compared the creativity measures of the non-creative robot condition (R_C-) to the tablet-only condition (T_C-) to evaluate how the robot's *embodiment* influenced children's creativity.

In both games, results showed that children who interacted with the creative robot (R_C+) expressed significantly higher levels of creativity as compared to children that interacted with the non-creative robot (R_C-). This validated my hypothesis that children can model a social robot's *demonstration* of creativity, which was in conjunction with the *learning from demonstration* approach. In both the games, results showed that there was no significant difference between the non-creative robot condition (R_C-) and the non-creative tablet (T_C-) condition, which rejected the hypothesis that the robot's *embodiment* had an influence on children's creativity.

In order to evaluate if a social robotic tutor offering *creativity scaffolding* in the form of reflective questions, challenges, and prompts can foster creativity in children, I ran one comparison study with the WeDo 2.0 construction activity. I divided the participants into three equal-sized groups: 1. a creative robot group (R_C+), where the robot did offer *creativity scaffolding*, 2. a non-creative robot group (R_C-) - where the robot did not offer *creativity scaffolding*, and 3. a tablet-only group - where the robot was not present (T_C-). Results showed that children in the creative robot group expressed significantly higher creativity scores than the other two groups, but no such significant difference was found in the tablet-only and non-creative robot conditions. Hence, it was the *creativity scaffolding* offered by the social robot, and not merely the presence of an embodied robot, that lead to creative gains in children. This validated my hypothesis that *creativity scaffolding* offered by a social robotic tutor can positively influenced children's expressed creativity in the task.

Hence, I suggest and validate interaction patterns for social robots used as pedagogical tools in classrooms that can help foster creativity in children. These are valuable interaction patterns to incorporate for researchers and educators designing embodied pedagogical tools that not only focus on children's cognitive gains, but also aim to enhance their learning behaviors such as creativity.

1.3.3. Design Guidelines for Robot Interaction Patterns to Foster Creativity

Finally, I offer design guidelines for roboticists and interaction designers to design robot behavior that helps foster creativity in young children. I use the learnings from the user studies I conducted and suggest interaction patterns that can be incorporated in future designs of social embodied agents. I suggest the following guidelines that foster creative thinking:

- Nature of the task : Design open ended playful tasks and collaborative child-robot that afford creative expression.
- Diversity of the task : Designing a diverse set of tasks that afford different types of creativity.
- Collaboration : The robots role must be a collaborative peer or tutor and not competitive.
- Creativity demonstration : The robot should itself exhibit creativity in the context of the task.
- Reflective questioning : The robot must ask children reflective questions about actions they take in the task.
- Challenging : The robot must present the child with optimal challenges during the task.
- Positive reinforcement : The robot must offer positive reinforcement to the children when they generate creative ideas.
- Rapport building : Building a social rapport and establishing common ground with the child.
- Positive affect : The robot must exhibit positive affect since it is positively correlated to creativity.

Chapter 2 : Background

2.1. Creativity

2.1.1. Defining Creativity

There are several frameworks of defining creativity, and what qualifies as creative behavior. In a review of Creativity literature, Peter Meusburger claims that creativity and creative thinking have been defined in over a hundred different ways [69]. From his work on the Structure of Intellect Model (SOI), Guilford suggested three basic components as factors of creativity: fluency, flexibility, and originality [19]. These three factors are still commonly acknowledged as basic components of divergent thinking. This work was influential in the development of the different definitions of creativity [12, 34, 41, 48], as well as development of standardized tests of creativity and divergent thinking [11, 34, 37, 51]. Modern researchers describe creativity as the process of generating artifacts or ideas, that are novel to the person, to the person's environment or to the world, that generate surprise, and that add value to the system [6, 33]. For the purpose of this work, I define creativity as the process of generating ideas that are novel as compared to the child's previous ideas, and that add value to the problem being solved. Novelty refers to generating ideas that are different from the ideas of their peers, and as compared to their own previous ideas. This involves mapping all ideas presented by the individual over time, and ideas presented by all individuals. Value refers to generating ideas that add value to the problem being solved. This includes solving problems in the most optimized way, or using least time and resources to solve a problem.

Creativity is also categorized in terms of the "four P's of creativity", that reflect the cornerstones of creativity research. These four P's are the Person (covers information about personality, intellect, temperament, physique, traits, habits, attitudes, self-concept, value systems, defense mechanisms, and behaviour), Process (relates to motivation, perception, learning, thinking, and communication), Product (when an idea becomes embodied into tangible form), and Press (or environment, and refers to the relationship between human beings and their environment) [38]. Guilford defines creativity as the embodiment of thought in the form of external behavior, consisting of three characteristics: fluency, flexibility, and originality. Creativity is also expressed in different forms - figural creativity (eg. drawing, painting, sculpting) and verbal creativity (writing, storytelling, composition, discourse) [68]. Creativity is also often viewed in conjunction with divergent thinking, which is the potential for original thought [41]. For the purpose of this study I refer to commonly accepted definitions of creativity in literature outlined in Table 1.

Guilford [68]	1957	Creativity is defined as the embodiment of thought in the form of external behavior, consisting of three characteristics: fluency, flexibility, and originality.
Torrance [52]	1998	Creativity is viewed as a series of flows, including problem identification, speculation, construction of hypothetical assumptions and creation, and the sharing of ideas with others.

Amabile [1]	1990	Creativity is regarded as the interaction between the individual and its external environment, including three components: domain- relevant skills, creativity-relevant skills creative-thinking skills, and task motivation.
Sternberg, Lubart [107]	1996	Creativity is perceived as an ability that everyone has, though with varying levels that are affected by the combination of six types of different and interrelated elements: intellectual abilities, knowledge, thinking styles, personality, motivation, and environmental elements.
Mumford [108]	2003	Creativity involves the production of novel, useful products.
Boden [6]	2004	Creativity is composed of Psychological and Historical creativity: P-creativity involves coming up with a surprising, valuable idea that's new to the person who invented it; an idea is H-creative if no one else has had it before and it has arisen for the first time in human history.
Baer and Kaufman [109]	2005	Creativity is explained through the lenses of the Amusement Park Theory that states intelligence, motivation, and a suitable environment, are necessary prerequisites of creativity.
Sawyer [110]	2011	Creativity is understood in the context of a group emergence where flow, collaboration, and improvisation processes take place. When group synchrony is reached, it becomes difficult to discriminate the individual contribution of each person, as "the whole is greater than the individual parts."
Cronin Loewenstein [111]	2018	Creativity is a process of following cues to generate insights that change our perspectives, which with the craft we can use to form inventions and enlightenment.

Table 1: Definitions of Creativity in Literature

For the purpose of this study, I limit the definition of creativity as the ability for novel idea generation. Specifically, I term the ability to generate ideas with greater fluency, flexibility and originality as creative thinking. I also categorize the ability for divergent thinking, or not conforming to the typical ideas as creativity. Further, I categorize activities that involve some amount of creation of artifacts, verbal, figural or structural, as activities that afford creativity.

2.1.2. Creativity in the Classroom

Using measures of divergent thinking, Torrance [52] was one of the first to show that students' creativity began to decline around age 6, slumped further in the fourth grade, but later showed a subsequent increase. This phenomenon became known as the fourth-grade slump [Figure 1]. This decline in creativity has been found to be evident in as many as seven countries worldwide [51]. Smith and Carlsson [45, 46, 47] found that after entering school, a slump in creativity occurred at ages 7 to 8. One suggested reason for this slump is a structured school curriculum with a lack of play-based learning activities, such as those in kindergarten [40, 51]. This drop in creativity, often referred as the fourth grade slump, may reflect the pressure to conform that categorizes educational settings [42]. Guilford [19] first noted how educational practices did not correlate well to children's creative thinking capacities. Previous research has elaborated the benefits of integrating creative skills into the educational institutions' curricula, and increased learning benefits [42]. Benefits of play-based learning approaches, and how it fosters child creativity have long been known [35].

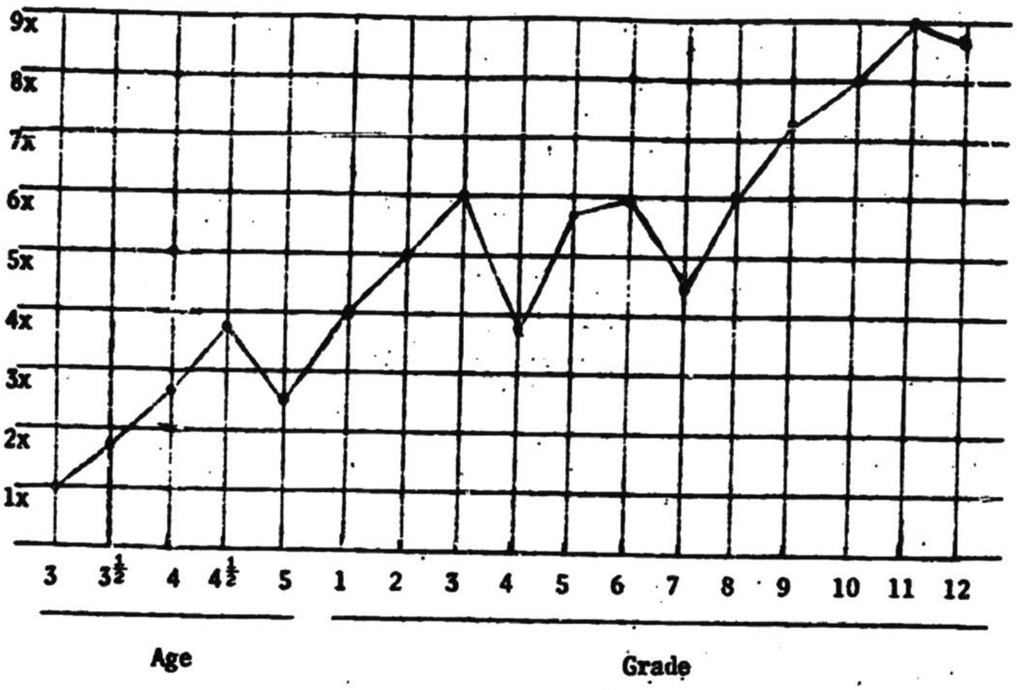


Figure 1. Creativity slump in grade 4 as measured by the Torrance Test of Creative Thinking (TTCT) [51]

It has been suggested that there are several external factors in classrooms, including their social interactions, that can contribute to fostering creativity in children. Amabile & Gryskiewicz [2] and later Witt & Beorkrem [57] identified the following "situational influences on creativity": freedom, autonomy, good role models and resources (including time), encouragement specifically for originality, freedom from criticism, and "norms in which innovation is prized and failure not fatal". Children's motivation and personality interact with the environment and components of the creative process to enhance the development of creativity in a child [13]. Other creators in children's environment including teachers and peers also act as potential models for creativity [42]. Creativity is also promoted when activities are presented in permissive and game-like fashion [53]. Furthermore, in learning contexts, it has been suggested that interactions with peers, and tutors, such as collaboration, question asking, reflection, greatly influence children's creativity [23, 20]. Zheng et al. [59] demonstrated how question prompts administered to children during different stages of a creative activity were influential in increasing students' creativity. Research in creativity learning outlines how learning environments must facilitate reflection to foster creativity learning [21]. There have been several efforts towards creating Creativity Support Tools, especially in the form of Graphical User Interfaces (GUIs) [44]. Given that robots are increasingly being used in education, and have been shown to be effective learning tutors and companions [4], this work aims to explore whether social interactions with robots can help foster creativity in children via peer to peer interaction.

2.1.3. Creativity Assessment

Even though creativity remains challenging to measure empirically, researchers have developed creativity assessment tasks with coding systems that conceptualize and measure creativity empirically. Popular standard assessments of creativity include: 1. the Torrance Tests of Creative Thinking (TTCT) [51]; 2. the Creativity Assessment Packet (CAP) [89]; 3. 3 subtests of divergent production from the Structure of Intellect Learning Abilities Test; 4. Thinking Creatively with Sounds and Words; 5. Thinking Creatively in Action and Movement; and 6. the Khatena-Torrance Creative Perception Inventory [9]. Commonly used in schools, the CAP includes the Test of Divergent Thinking, and the Test of Divergent Feeling which builds on top of the idea of the cognitive-affective model of creativity [54]. There are also several task based assessments such as the Droodle Creativity Task [24] which ranks creativity based on participants' ability to generate surprising and witty titles for abstract images, the Unusual Uses Task [82] which ranks creativity based on participants' ability to think of alternate uses of an object, and the Candle Problem [13]. Tests of creative thinking may also be specific to the type of creative expression, for example, Test for Creative Thinking-Drawing Production (TCT-DP) [83] is used to measure figural creativity from drawings, whereas tests such as Unusual Uses Task, or Droodle Creativity Task are used to measure verbal creativity.

In this work, I made use of existing validated creativity assessment measures for assessing children's creativity pre-interaction, as well developing creativity measures during the interactions. I used the Torrance Test of Creative Thinking (TTCT) for assessing children's verbal and figural creativity before all interactions and to divide them in balanced study groups. I used the Droodle Creativity Task's coding system to assess creativity in the Droodle Game. I used the TCT-DP to assess figural creativity from children's drawings in Magic Draw. Assessment of creativity in the WeDo construction task is inspired from the Unusual Uses task, as well as from tests of Divergent Thinking. Task based assessments help me integrate existing validated creativity assessment in fun game-based tasks, while using them as *stealth assessment* measures to assess children's creativity during the tasks [80].

2.2. Human-Robot Interaction and Creativity

Artificial embodied agents such as social robots have been studied to be effective pedagogical tools for young children leading to both cognitive and affective gains [4]. There has been some work that focuses on using social robots as a means to foster creativity in adults and children.

The use of robots in the classroom to foster creativity in children is not new. Lego Mindstorms, Bots Alive, Cozmo, Pop bots [7, 10, 31, 56] are examples of robot construction kits aimed to teach children about robotics and allow for creative expression. Alves-Oliveria et al. [51] built Yolo, a robot to be used by children as a tool to boost new ideas and stimulate their creativity. These works, however, uses the robot as a toolkit that children *use* to create, rather than as an agent that children *interact* with. Using social interactions of virtual and physical agents have previously been used to stimulate creativity. Fischer and colleagues [15] embedded a software agent into an architectural design tool. The agent offered critiquing statements to promote a reflective design practice. Jung et al. [22] demonstrated how having a reflective conversation with an embodied artifact in the making positively influenced the learning process. Kahn et al. [27] explored if a social robot helps engage adults in creative tasks. They categorize the robot's interactions with people into several interaction patterns - introduction of the task, defining the creative space, evaluating similar experiences, forming an inventory of ideas, reflecting on intuition, pushing the limits, considering alternatives, building on foundational work, validating decision, engaging in creative conflict, and breaking loose. They found that participants engaged in creativity tasks longer and provided almost twice the number of creative expressions in the presence of the robot as compared to a PowerPoint presentation which displayed the same instructions. These results help us understand that a robot's social interaction has the potential to motivate adults to come up with creative expressions. However, no such work has been conducted for analyzing the effect of robots' social interactions on children's creativity. In my work I look to use a similar scaffolding paradigm, only reduced in complexity, to assess if this holds true for Child-Robot Interaction. Hence, I suggest interaction patterns of social robots specific to a computational learning setting that aim to foster creativity. These are described as *Creativity Scaffolding* interactions in the future sections.

Social robots have previously been used as learning tools to foster positive learning behaviors, such as curiosity [18, 36], growth mindset [36], grit, persistence, attentiveness [4], etc. Several studies have looked at how children model a social robot's learning behavior, such as curiosity or growth mindset. The physical presence of a robot tutor increases cognitive learning gains [32]. Gordon et al. demonstrated how children can socially emulate curiosity from a curious robot, and exhibit greater curiosity related behaviors such as question asking while interacting with a curious robot as compared to a non-curious robot [18]. Park et al. demonstrated how a robot exhibiting growth mindset can help foster a growth mindset in young children [36]. In a similar theme, in this work, I aim to explore if a robot exhibiting creative thinking can help foster creativity as a learning behavior in young children. Hence, I suggest a set of novel verbal and non-verbal interactions as well as gameplay behaviors of social robots that exhibit its creative behavior. These are described as *Creativity Demonstration* interactions in the future sections.

Hence I suggest two ways in which social robots can motivate a child to be more creative, by exhibiting *Creativity Scaffolding* behaviors and *Creativity Demonstration* behaviors.

2.3. Game-Based Learning

According to Klopfer, Osterweil, and Salen, games refer to structured or organized play [106]. Many researchers have drawn attention to the close association between play and creativity. From diverse theoretical perspectives it is accepted that play is the first creative activity of the child and that imagination originates and develops in play. Creative play in its different forms is of great importance in development because it stimulates curiosity, flexibility, and improvisation and promotes problem-solving behavior that leads to learning, imitation, and adaptation to change. Research that has analyzed the contributions of play to child development has stressed the crucial role of play in human development. Many studies carried out within different epistemological frameworks have confirmed that play stimulates creativity [53, 94, 95, 96, 97], identifying play as a predictor of divergent thinking. In the kindergarten approach to learning, Resnick [81] emphasizes the significance and centrality of play in creative learning, and how it has a positive influence on both children's motivation to learn as well as their learning gains.

Games are a proven medium for effective concept learning as well as for fostering creativity [43]. Several behaviors that constitute creativity can be afforded via game-play behaviors, such as generating multiple ideas to solve a problem, generating novel ideas that add value to a solution, metacognition, asking questions, and cross-contextual thinking [21]. As many researchers have argued, games can act as transformative digital learning tools to support deep and meaningful learning. Based on the situated learning theory [104], learning in a mindful way results in knowledge that is considered meaningful and useful, as compared to the inert knowledge that results from decontextualized learning strategies. Games designed with the specific intention of changing players' behaviors, attitudes, or knowledge during and after play are referred to as Transformational Games [105]. In this work, the behavior we are targeting is creativity. Digital games, especially those categorized under the genre of Sandbox games such as Minecraft [14] often provide opportunities for generating new artifacts, allowing for creative expression. Learning games are an effective medium to teach concepts to children since their *fun* nature ensure higher engagement levels. However, for games to effectively foster creativity as a learning behavior, it is imperative to ensure that the game mechanics allow for creative expression and creative problem-solving. Games can potentially allow generation of content by the player as a part of the game mechanics. In a strategy game, game mechanics such as the ability to deploy multiple strategies, rewarding novel strategies, facilitating reflection of strategies, and providing agency help foster creativity. Mechanics such as fixed gameplay, competitive environments, and low difficulty levels might inhibit creativity. Yeh et al. [58] demonstrate how positive, high-activation, and promotion focused emotions induce creativity while playing games, whereas negative, high-activation, and promotion focused emotions inhibit creativity. Isen et al. [62] demonstrate how positive affect facilitates creative problem solving, and games have been shown to induce positive affect in children. Hence, providing appropriate challenges to induce highly-activated and promotion-focused positive emotions are critical for the success of games designed to improve creativity. In this work, I chose the theme of the game-based activities and the game mechanics to afford creativity, as described in the following sections.

Chapter 3 : Designing Child-Robot Interaction Design for Fostering Creativity

Studying the creativity literature, I learned that creativity in classroom tasks is influenced by several external factors, one of which is the nature of the task itself [64]. In order to understand the role that robots can play in fostering creativity in children, I designed game-based child-robot interactions that afford creativity as a gameplay behavior. As I outline in the background section above, creativity is closely associated with play. Game-like interactions can elevate creative expression, especially in children. There is an extensive body of research supporting the efficacy of game-based learning interactions [84]. Further, game-like activities make the interactions seem less like tasks, and more fun. I first brainstormed several different interactions that can allow for creative expression. This process involved both, looking at existing games and tasks, as well as generating new ideas of games that involve some level of *'creation'* and/or *'problem solving'*. I studied games such as Minecraft [14], SimCity [85], and Roller Coaster Tycoon [86], which involve creation of simulated worlds. These games allow for creative expression since the player can construct infinite worlds, but are constrained in terms of the kinds of building blocks players can use. Further, simulation games allow for creative problem solving where players need to sustain their world using limited resources.

I also studied games which afford different types of verbal or figural creative expressions such as Wordid [87] and Pictionary [88] in which generation of verbal and figural artifacts are central to the gameplay. Further, I looked at toolkits commonly used in creative play, such as Lego Mindstorms, Makey Makey, Lego WeDo construction kits, littleBits, etc. which involve modular building components that can be repurposed to be used in several different ways. These kits often make use of hands on construction, and help children learn about physics, electronics or computational logic. I also looked at digital tools, such as the visual programming language Scratch [75], Blockly games [90], Snap [91] and GDevelop [92] that provide tools for children to *create* games and experiences programmatically. I learned that these maker kits and programming environments provide modules (such as blocks), that can serve a kind of function (such as connector, or condition), but can be used in many different ways and locations, hence allowing children infinite possibilities for their creations. Further, several of these tools provided platforms to help children *share* their creations, which is an essential part of creative learning [81]. I also looked at tasks used in the assessment of creativity, such as the Candle Problem task [13], the TTCT figural task [51], the TTCT Unusual uses task [51], and the Droodle task [24], that often afford creativity, as inspirations for game mechanics.

Among different variables that influence creativity development – collaboration, defined as a group of people working towards a common goal by interacting with each other, is known to be one of the most influential factors [65]. Further, children's social interactions with peers and tutors while collaborating have been shown to boost creativity [25]. Sociocultural researchers view creativity as a potential outcome of collaborative interactions in open-ended, student directed, learning environments [66, 67]. However, personalized learning tools, that involve one-on-one learning, often miss out on this benefit of collaborative learning. Hence, I decided to keep collaboration with peers in mind while designing these interactions, where the collaborator would be the social robotic peer or tutor. I began with brainstorming several game-like interactions that were inspired from other games and tasks, with social robotic peers and tutors, some of which I mention below:

- Pictionary
    - Gameplay: Players play a drawing and guessing game where one player draws an image and the other one guesses the image, like classic Pictionary. Then they switch the drawer-guesser roles.
    - Role of the robot: The robot acts as a peer that takes turns with the child to make drawings.
- Robo-platform
    - Gameplay: Player constructs a video game course for a virtual game agent to solve.
    - Role of the robot: The robot acts as a peer that plays the main game, while the child sets up the platform such that it can solve the levels. The robot offers ideas and suggestions.
- Ultimate machine
    - Gameplay: Player constructs a contraption in a gravity enabled world that helps a virtual player reach the final goal.
    - Role of the robot: The robot acts as a peer that plays the main game, while the child sets up the platform such that it can solve the levels. The robot offers ideas and suggestions.
- 20 questions
    - Gameplay: One player thinks of a famous person or character, and the other player asks 20 questions to guess who the person is. Then the players switch turns.
    - Role of the robot: The robot acts as peer that takes the guesser role or the asker role.
- Who am I
    - Gameplay: Players train the character of a robot with word phrases. For instance, they teach it phrases that it likes and phrases that it dislikes, or, phrases that are scary and phrases that are safe, or phrases that are funny and phrases that are not. Players teach the robot to react to different classes of phrases in certain ways. Another player then presents the robot with new phrases to test out its character.
    - Role of the robot: The robot is used as a tool in the gameplay and acts as a trainee that the children train to react to different phrases.
- Closest word
    - Gameplay: The goal of the game is to converge on a certain word. Players start with saying their own words, and then slowly try to converge to a middle word that is the same. For instance, if players start with orange and round, converging words could be orange or pumpkin. The goal is to converge in as few rounds as possible.
    - Role of the robot: The robot acts as a collaborative peer trying to converge to a word with the child.
- Interactive drawing game
    - Gameplay: Players collaboratively make drawings. They start with an abstract graphic and take turns to make a complete drawing.
    - Role of the robot: Collaborative peer who makes parts of the drawings.
- Interpolating drawing game
    - Gameplay: One player draws two drawings and the other player makes middle drawings to interpolate one into another.
    - Role of the robot: The robot acts as a peer trying to make middle interpolations.
- Construction game
    - Gameplay: Players collaboratively form a physical worlds with blocks such as LEGO.
    - Role of the robot: Collaborative peer that offers ideas of construction.
- Physical contraption building

    - Gameplay: Similar to the construction game, but with the goal of making physical contraptions to make a ball reach a certain goal. Players can use a variety of craft materials for construction.
    - Role of the robot: The robot acts as a mentor and offers *creativity scaffolding* to the child by providing ideas and solutions to problems.
- Recipes
    - Gameplay: Players come up with creative recipes using a limited number of ingredients.
    - Role of the robot: Collaborative peer that offers ideas of recipe.
- Storytelling from visual and verbal prompts
    - Gameplay: Players are given a few images and words, and are tasked with stitching them together into a meaningful story.
    - Role of the robot: Collaborative peer that participates in storytelling.
- Infinite stories
    - Gameplay: Players start with one sentence and build stories on top of each other's sentence additions.
    - Role of the robot: Collaborative peer that participates in storytelling.
- Droodle game
    - Gameplay: Players take turns to come up with humorous titles for abstract images.
    - Role of the robot: The robot acts as a peer that generates titles for the given images.
- Cannibals
    - Gameplay: Players are presented with different combinations of cannibals and travellers similar to the traditional cannibals game. They need to enable them to cross a river.
    - Role of the robot: The robot acts as a mentor that provides scaffolding when the child is struggling or needs more ideas.

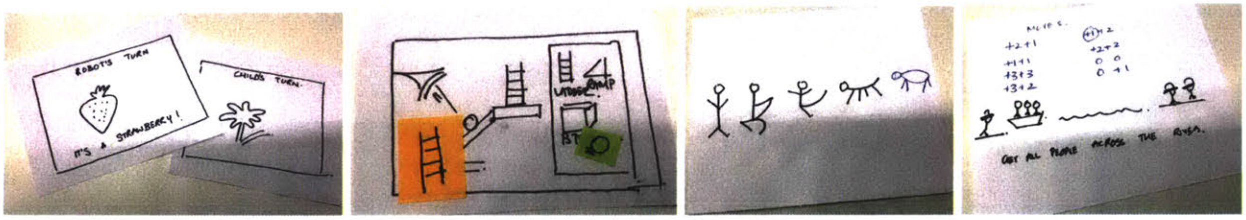


Figure 2. Early stage paper prototyping of game ideas for brainstorming.

I first wrote one-page game mechanics for each of these games and took feedback from my advisor and readers. They offered feedback about how certain game ideas, such as 20 questions, involved less creative freedom, and how very open ended games, such as infinite stories might be challenging to build and assess. I produced low fidelity paper prototypes of these game concepts, and playtested them with peers [Figure 2]. Based on the players' perception of how fun and playable these interactions were, I scoped down and combined these ideas into four concrete game concepts. I designed four child-robot collaborative games that afford different types of creativity as a gameplay behavior : 1. Droodle Creativity Game, that affords verbal creativity in the form of imaginative dialogue, 2. Magic Draw, that affords figural creativity in the form of drawing, 3. WeDo 2.0 with Jibo, that aims to foster construction creativity, and 4. Escape adventure, that affords divergent thinking and creative problem solving. In each of these games, children collaborate with a social robot to reach a common goal. All games were playtested and iterated to be more child friendly, fun, playable and foster creative thinking. For all the four games, I used

Jibo as the social robot platform elaborated below, followed by the detailed design of each game, and how I plan to assess the creativity of the player in each game.

3.1. Robotic Platform

The social robot platform used for this work was the Jibo SDK [20][Figure 3.a.]. Jibo is a socially expressive companion robot that has a three-axis body and a screen based face. Jibo is made out of aluminium and is 11" tall and 6" wide. It has three-revolute axes and an HD LCD touchscreen. Jibo was designed to be a social robotic companion for the home and is also used as a research platform to understand how people interact with robots in the real world. Jibo uses a text-to-speech service for speech generation, and a speaker for sound output. Jibo also has a microphone to identify speech, cameras to detect images, and tactile sensors to detect touch. For the purpose of these games, I only made use of the microphone and the speaker. While Jibo is designed to be male in gender, I tried to make the interactions gender neutral and did not specify the robot's gender anywhere during the interactions. I make use of Jibo Developer Toolkit's Android module for setting up communication between an Android tablet and the robot while they are on the same network. The AppToolkit enables me to use hundreds of animations and expressions on Jibo, including all basic emotions and expressions: Joy, Sadness, Excitement, Anger, Frustration, Confusion, Curiosity, Laughter, Attention, Surprise and Fear. I can display images and emoji of common objects on Jibo face. It also enables me to make Jibo look in a certain direction and use its sensor data (microphone, camera and touch sensor). The games' logic lives on the Android applications, which communicates with the Jibo platform [Figure 3.b.] using the AppToolkit communication protocol which is hosted on the MIT server and is password encrypted. The choice of using Jibo as a robotic platform was because of several reasons:

1. Character design: The Jibo robot is designed to be a friendly, playful and child-like peer robot. This character was ideal given that I aimed to make game-like interactions for children. Jibo emotes through bodily animations and facial expressions that helped me design it into a realistic peer-like gameplay.
2. Stability: The Jibo SDK is stable enough that I was able to have children play games with a fully autonomous agent without any human intervention.
3. Software Development Kit (SDK): The Jibo AppToolkit enabled me to develop Android and Unity games and connect them remotely with Jibo. Hence, I could build in robot interactions seamlessly into gameplay, and have the robot be fully autonomous.
4. Robot Operating System (ROS) Compatibility: In the *creativity scaffolding* task, instructors control Jibo remotely using a desktop interface. I use ROS communication protocol for this communication and Jibo is compatible with ROS.

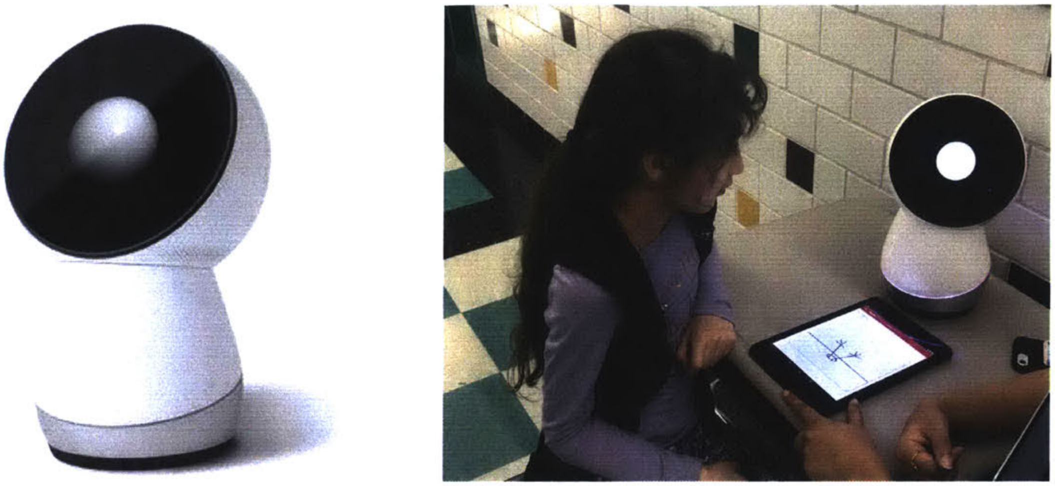


Figure 3.a. Jibo is a social robot for the home and a research platform used by MIT to understand how people interact with robots. 3.b. Child interacting with the Jibo robot and playing a game developed with the Jibo AppToolkit framework.

Figure 4. Different poses of the Jibo robot that enables the generation of animations and emotional expressions.

3.2. Droodle Game Interaction Design

Creative expression is often categorized as verbal and figural creativity [68]. Verbal creativity is manifested in the form of storytelling, dialogue, discourse, poetry or communication. We designed this collaborative game for children to express verbal creativity through imaginative dialogue. The game requires players to express fluency, flexibility, originality and elaboration of ideas through coming up with creative titles for Droodles. A Droodle is a simple abstract drawing [Figure 5] that "comes into focus" (in a surprising way) with the addition of a clever title. Droodles was a syndicated cartoon feature created by Roger Price and collected in his 1953 book Droodles, though the term is now used more generally of similar visual riddles [98]. Figure 5 provides examples of some Droodle images with associated titles.

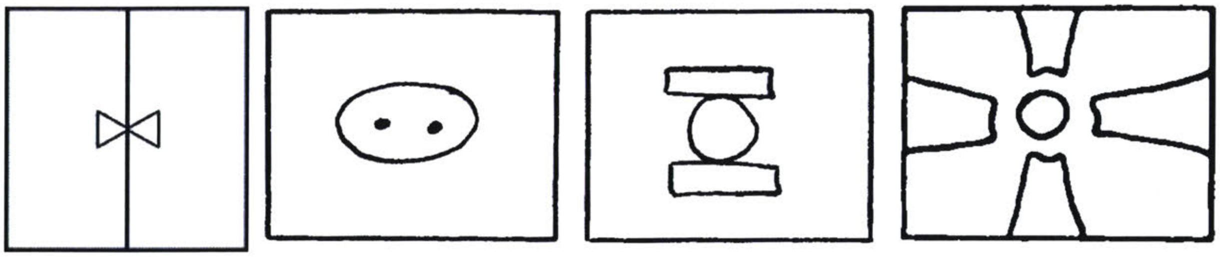


Figure 5. Man wearing a bow-tie caught in elevator doors, Pig emerging from a heavy fog, tomato sandwich made by an amateur chef, Four elephants are inspecting an orange

3.2.1. Game Design

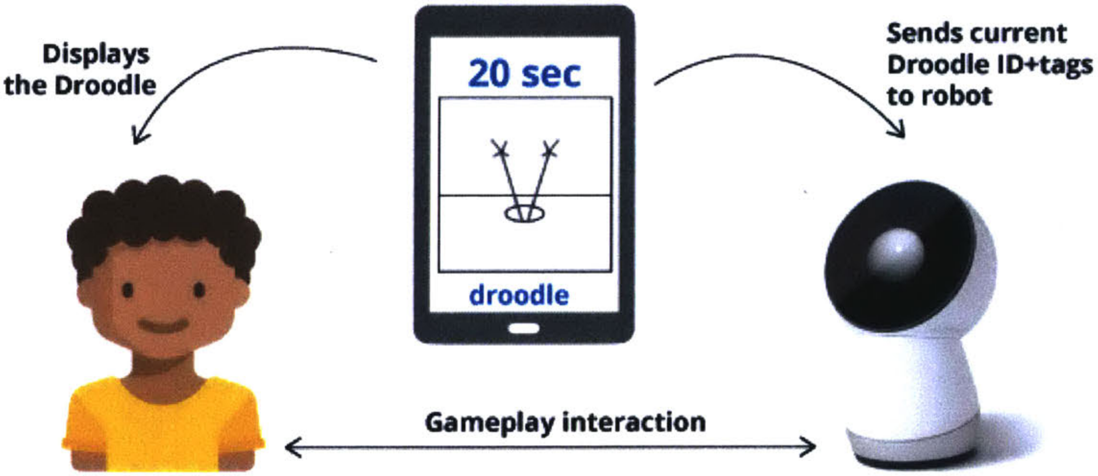


Figure 6. System Components. The child and the robot play the Droodle game collaboratively. The Droodles are displayed on the Android tablet. The tablet communicates the current Droodle ID and titles to the robot.

In order to understand how interacting with a robot influences children's creativity, I designed the Droodle Creativity Game that affords creativity as a gameplay behavior. The Droodle Creativity Game is inspired from the Droodle Creativity Task developed by Kahn et al. [24], which is a verbal creativity task that draws upon people's ability to use language in witty and creative ways (Droodle titles) to describe an abstract image or figure (Droodle). Kahn et al. [24] developed a creativity assessment guideline for measuring the creativity of Droodles using qualitative coding. The coding method takes into account the coders' initial reaction, pattern matching, categories and rationale, and overall assessment, to score Droodle titles as high, medium, low, or non-droodle. Further, the coding guide also offers prototype Droodles and coded Droodle titles with rationales behind their scores. There exist some variations of the Droodle Task, such as the Modified Droodle Creativity task, where the participants draw their own Droodle and come up with a creative title, that have been used for an assessment of creativity.

Participants are presented with a Droodle, and they are tasked with generating Droodle titles. The Droodle Task coding system provides a comprehensive guide to rank the titles provided by participants as 'non-droodle', 'low-', 'medium-', or 'high-droodle' by the coder based on their initial reaction, pattern matching, and categories and rationale. For instance, in Figure 7.b. an example low-Droodle phrase would be, *'2 lines and 4 circles'*, and a high-Droodle phrase would be, *'A bear climbing a tree'*. In addition to these verbal interactions, the robot also showed multiple expressions of thought and curiosity, and expressed surprise and excitement upon coming up with creative titles. As a child friendly, game-like, fun activity, the Droodle Creativity Task is well situated to measure creativity in young children.

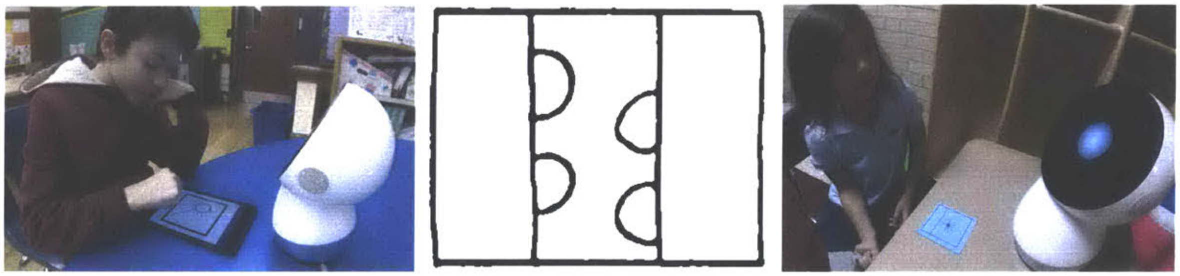


Figure 7. (a) Interaction Scene. A child is playing the Droodle Creativity Game on an Android Tablet with the social robot Jibo. (b) Example of a Droodle Image. 10 Droodles were used in the Droodle Creativity Game (5 per player). (c) Low fidelity prototype developed for the pilot study which used paper droodles.

For this study, I developed an interactive game inspired from the Droodle Creativity Task. The child and the robot take turns playing the game [Figure 7.a.]. The active player is presented with Droodles on a tablet screen and they come up with droodle title(s) in 30 seconds. Then the turn shifts to the other player until each player has played five turns each. Droodles used in the task were taken from Droodles: The Classic Collection [33], which also includes a library of droodle titles.

Prior to developing the tablet game, I ran a pilot study with nine participants using paper cards for Droodles [Figure 7.c.]. This was done to playtest the interaction using a low fidelity prototype and ensure that the game is fun and playable. I observed that the Droodle task is a fun age appropriate task and all nine children could successfully complete the interaction with the robot. All nine children reported the game to be fun. Eight out of nine children said that they thought that Jibo had creative ideas. I learned that children find the game fun upto five rounds, after which it becomes tiring and less novel. I also observed gameplay nuances like children inverting the image for the robot to see, keeping time, and offering feedback about the robot's ideas which are gameplay dynamics I incorporated in the game design and robot interaction.

3.2.2. Interaction Scenario

3.2.2.1. Robot Introduction

Children are first introduced to the robot by the experimenter as a peer that they would be playing the game with. The robot then engages in a short self-introduction and asks participants to introduce themselves.

Robot: *"Hi, my name is Jibo. I am a social robot. What is your name?"*

3.2.2.2. Task Introduction

The robot explains the gameplay to the participants.

Robot: *"I have a fun game for you today. Do you want to play with me?"*

Child: *"[Yes]"*

Robot: *"Do you like telling stories?"*

Child: *"[Yes]"*

Robot: *"We will look at some pictures, and try to think of funny and creative ideas about what they are. Let your imagination run wild. Come up with as many ideas as you can in 30 seconds. Let me show you an example."*

The tablet app displays an example droodle selected from our library of Droodles, and the robot responds with a Droodle title. After the example Droodle, the robot is ready to start the game.

Robot: *"Are you ready to start the game?"*

Child: *"[Yes/No]"*

The participants can respond with a *"Yes"* or *"No"* using speech or UI buttons on the robot's screen. If the participants respond with a *"Yes"*, the robot begins the game. If the participants respond with a *"No"*, then the robot proceeds to provide a second example Droodle. If the participants respond with *"No"* more than once, experimenters intervene to help the participants understand the game until they are ready to play.

3.2.2.3. Child-robot Co-play

The robot and the participants take turns to play their rounds. In each round, the player is given a Droodle image on the tablet screen, and they have 30 seconds to say phrases describing the image. Participants can come up with as many phrases as they can. For every idea, the participants are required to press the idea button on the tablet screen, and record their idea. The tablet screen displays a timer and a counter for the number of phrases each player came up with. There is a total of 5 rounds. The rounds start with the robot's turn and the robot transfers the turns by using verbal phrases.

Robot [child's turn]: *"Now it's your turn. Come up with as many ideas as you can."*

Robot [robot's turn]: *"Now, it's my turn."*

After 5 rounds, the robot starts to terminate the game by saying goodbye.

Robot: *"Thank you for playing with me. I had fun! Did you have fun?"*

Robot waits 5 seconds for the child's response. Then it concludes the interaction.

Robot: *"It's time for me to go to sleep now. Bye!"*

The robot performs a *going to sleep* animation.

3.2.2.4. Robot Interactions

The robot acts as a collaborative peer that participants play the Droodle game with. The robot takes the role of explaining the gameplay to the participants, and providing an example. During the robot's turn, the robot picks Droodles from the Droodle library, which contains a list of strings, and each string has been coded with (1) the number of themes explored, and (2) a creativity score (non-, low-, medium-, or high-droodle). The number of themes explore were calculated using Rake NLTK, a Natural Language Processing Library [34]. The creativity scores are calculated using the Droodle Task Coding system [24]. The robot also engages in verbal and non-verbal interactions expressing wonder, curiosity, excitement and surprise. For instance, when the robot is attempting to think of a droodle idea, it says, "*I wonder what else it can be*", and has a *curious* expression in body posture and eye expression. During the child's turn, the robot engages in verbal and non-verbal expressions of *pride, joy*, and *surprise*. For instance, when the child generates Droodle ideas, the robot praises the child by using phrases such as, *"Great job*", "*I would not have thought of that.*", "*You are doing great*" and expresses *pride* and *joy*.

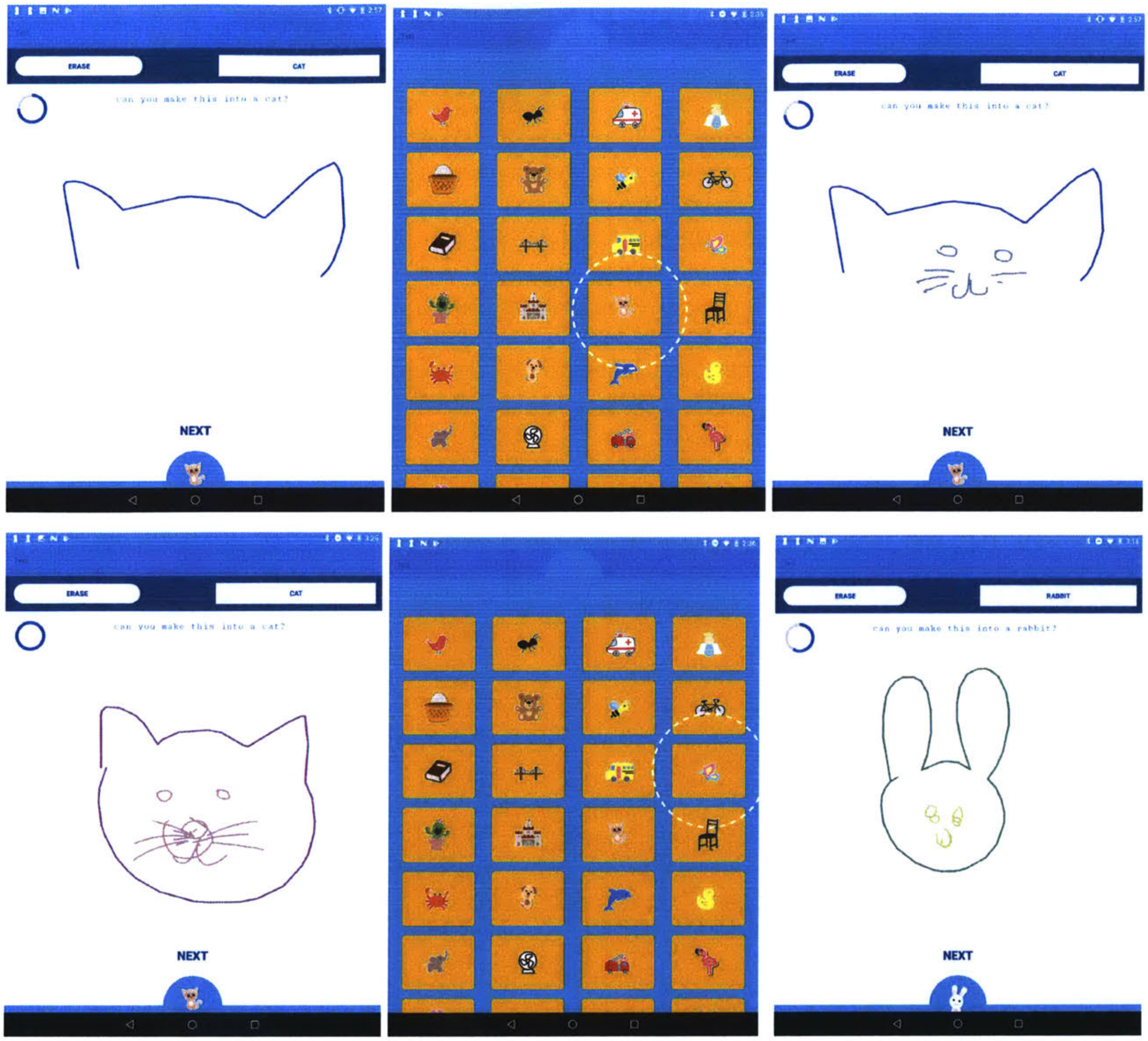
3.3. Magic Draw Game Interaction Design

Creativity is not only manifested in the form of verbal creativity, that is, storytelling, poetry, discourse and communication, but also in the form of figural or graphic creativity, that is the person's ability to draw, paint or sculpt. In order to afford figural creativity, I designed a collaborative drawing game that the child played with the robot [Figure 10]. The gameplay involves the children and the robot collaboratively completing a drawing of an object that either the robot chooses or the child chooses. The robot used for the game, Jibo, is a fully autonomous player in the game and involves no human control throughout the interaction.

The gameplay involves one player drawing a starting doodle (such as a circle) on a shared interface (in this case, a tablet screen), and prompting the other player to convert the doodle into a meaningful object (such as a cat). This gameplay requires the players to demonstrate divergent thinking while attempting to imagine one unrelated shape as a starting form of another object, as well as fluency of thought. It involves what Guilford terms as ideational fluency – the ability to rapidly produce ideas in succession; and associational fluency – the ability to generate artifacts to associate the starting prompts to the target object. Further, the game mechanic also allows that players can change the target object for the same prompt, or change the prompt for the same target object. This requires the other player to demonstrate flexibility of thought, that is come up with many different categories of ideas to solve the problem. The robot and the child take turns to make their drawings building up on the other's drawing. Since collaboration is known to strongly influence and motivate creative thinking, the gameplay is designed to be collaborative, where the game narrative states that the aim of the game is for the child and the robot to come up with a shared drawing.

3.3.1. Game Design

The gameplay of Magic Draw is illustrated in Figure 8 below. The game is played on a tablet interface since it affords drawing on a digital canvas using fingers and makes it convenient to capture drawings' stroke data. The child and the robot take turns to be player A and player B for 3 rounds of four minutes each (two minutes per player) before the game terminates.



can you make this into a cat?

can you make this into a cat?

can you make this into a cat?

can you make this into a rabbit?

Figure 8. Interface screenshots of the Magic Draw game explaining the child-robot gameplay. 8.a. The child draws a starting prompt (cat ears). 8.b. The child selects a target category (cat) 8.c. The robot tries to convert the starting prompt (circle) into the target category (cat). 8.d. The robot can save the image and draw a new one. 8.e. The child can select a separate category for the robot to draw (rabbit). 8.f. The child can clear the prompt a draw a new one. After the timer runs out, players switch turns. (*order : clockwise starting top-left*)

In order to design this collaborative drawing interaction, I needed to come up with a way for the computer to generate doodles that used the child drawn doodles as starting points. I designed a fully autonomous interaction, where the tablet generates drawings starting from the child's strokes to the final target doodle (such as a cat). I made use of Recurrent Neural Networks (RNNs) trained on human drawn images of 55 common everyday objects to generate these drawings. Taking inspiration from the Sketch RNN model developed by David Ha [70], I trained a new model on crude human-drawn images representing 55 classes from the QuickDraw Dataset [71], to generate unconditional images. Each class of QuickDraw is a dataset of 70K training samples, in addition to 2.5K validation samples, and 2.5K test samples. I also added to this a dataset of children's drawings that we previously collected. These 55 categories were chosen by a literacy expert based on what is age appropriate for children in the 6-10 year age group [Figure 12]. The model is a Sequence-toSequence Variational Autoencoder (VAE), which takes a vector sketch as an input and outputs a latent vector. The level of randomness of an output vector is controlled by a temperature variable τ, which essentially determines how random vs refined the output sketch vector is. In this work, I use Sketch-RNN to predict endings of incomplete strokes [Figure 9]. This is a method developed by Ha et. al [2017] where they use the decoder RNN as a standalone model to generate a sketch that is conditioned on previous points. The decoder RNN first decodes an incomplete sketch into a hidden state *h*. Afterwards, they generate the remaining points of the sketch using *h* as the hidden state. These completed sketches can also be controlled in terms of their randomness by using the temperature variable τ. Figure 9 shows decoder-only models trained on individual classes, and sample completions by setting $\tau = 0.8$. This is the same model I use for the game for the robot to complete the child's drawings. I modified the τ in different study conditions (creative versus non-creative robot) to modify the randomness and quality of drawings.

Figure 9: Sketch-RNN predicting possible endings of various incomplete sketches (the red lines) [Ha et al., 2017]

For the purpose of this interaction, I host a local server on a computer in the vicinity of the tablet, which runs the model. When the model is running during gameplay, the tablet sends and receives messages from the server which includes sending the starting prompt image and the category selected, and receiving the generated stroke image. The RNN generates new drawings around the starting prompt and sends it back to the tablet. The tablet also sends the selected category to the robot, and the robot responds with the category name. While the robot is not related to the actual doodle drawing itself, the robot animations (looking down at the tablet and responding to the target category selected) provides the impression that the robot is actively involved in the drawing purpose. Figure 10 illustrates the system components of Magic Draw and how they interact.

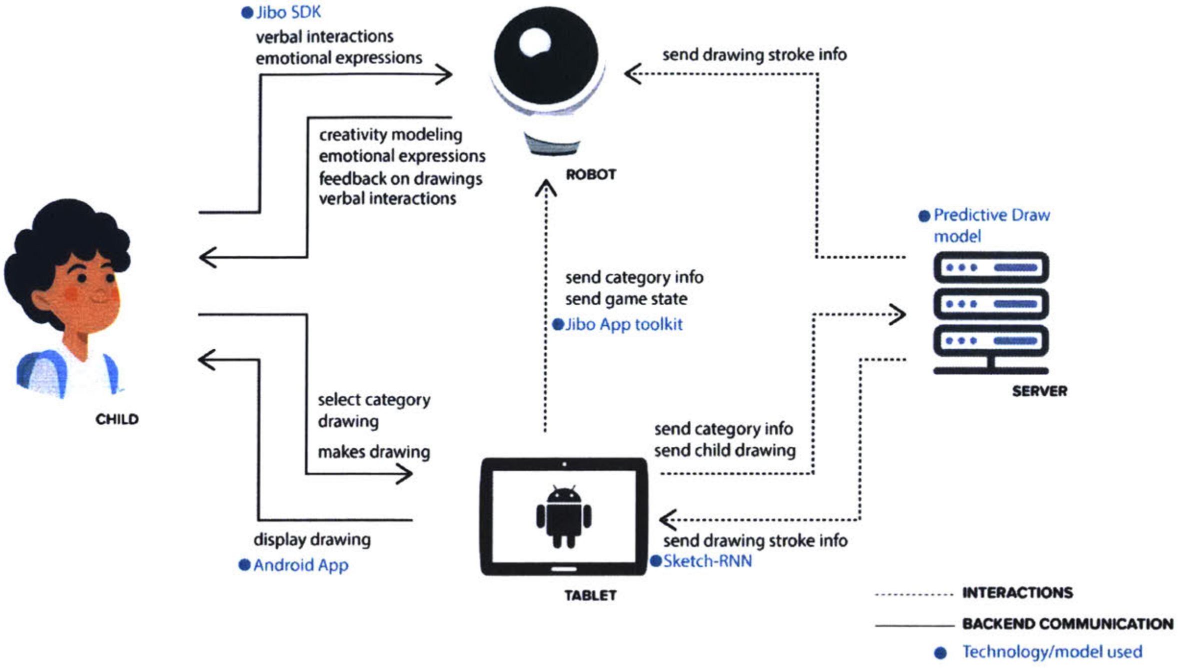


Figure 10. Magic Draw system components. Children interact with the robot and the tablet verbally and for making drawings. The robot and the tablet communicate with the server to send category information and receive drawing stroke information.

I iterated through some rounds of interface design for the tablet application based on early playtests with children [Figure 11]. Based on these pilots I learned that for children of the 6 - 10 year old age group, I should remove all words since some of these children are pre-reading and make use of icons instead. I also learned that it is beneficial to make the interface as simple as possible to make the drawing the central focus. Further, children were unhappy that their drawing would be interrupted in the middle when a round would end, so I incorporated a timer to notify them of when the round is about to end.

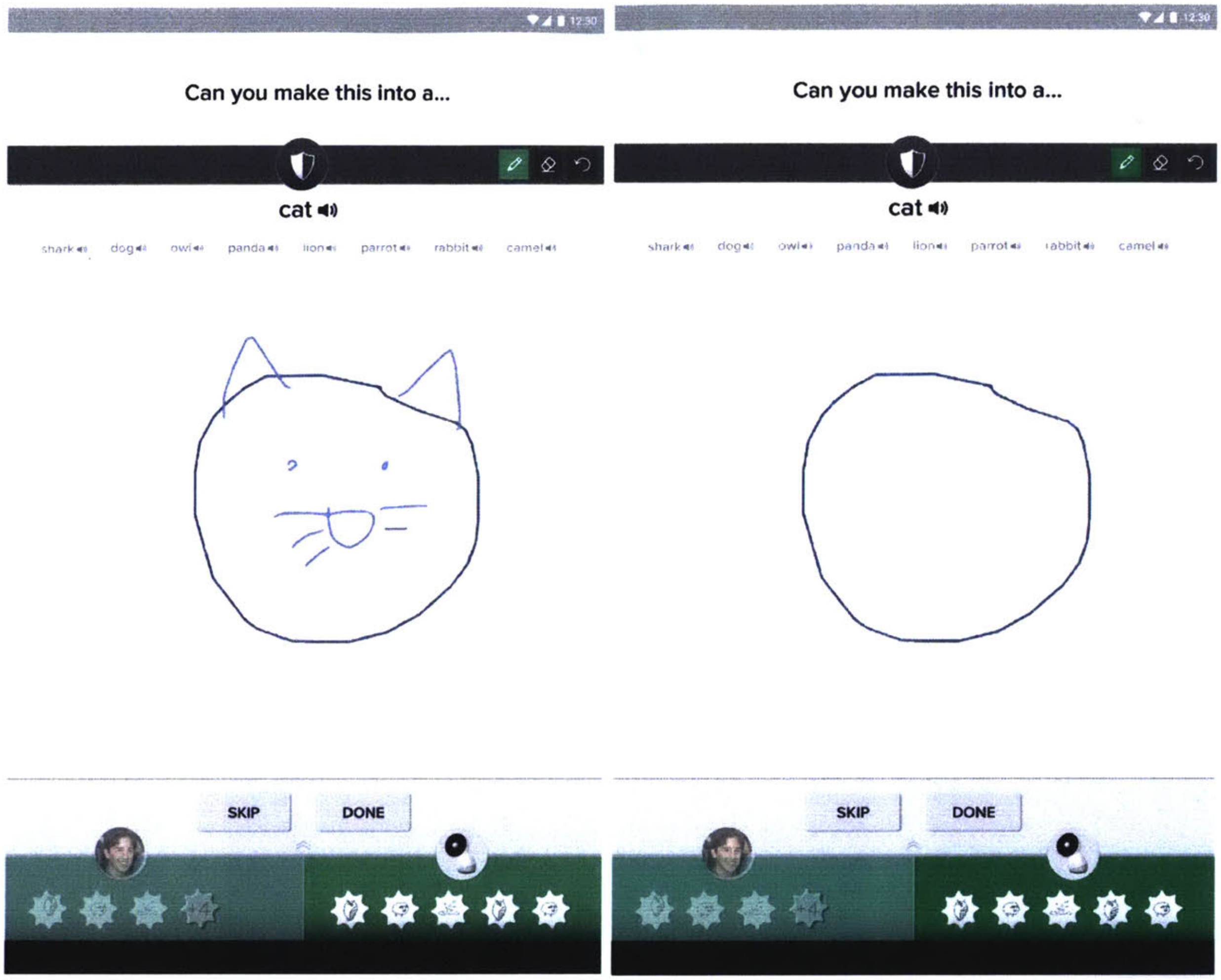


Figure 11. Early stage tablet interface design of the Magic Draw game

3.3.2. Interaction Scenario

3.3.2.1. Robot Introduction

If the children have played another game with the robot before, children are informed that they will be playing a new game with Jibo. If not, children are first introduced to the robot by the experimenter as a peer that they would be playing the game with. The robot then engages in a short self-introduction and asks participants to introduce themselves.

Robot: *"Hi, my name is Jibo. I am a social robot. What is your name?"*

Child: *"Chasity"*

3.3.2.2. Task Introduction

In my first pilot test, I did not introduce the task to the children, while assuming that it will be self explanatory what the interaction is. However, children were confused about when they should make the prompt versus when they should make the entire drawing. Further, I designed the game such that the robot starts drawing after the first stroke that the child makes and as soon as they lift their finger off the tablet. However, this was not intuitive for the children who kept drawing multiple strokes. These usability issues in game interactions were further enhanced by delays in the model's response due to network connections in schools. Hence, I redesigned the games with some level of task introduction.

In the current version of the game, the robot starts with introducing the game.

Robot : "*Hi Chasity. Welcome to Magic Draw. We will be making some drawings together. Are you ready to begin? Press begin when you are ready to start.*"
Child: "*Yes.*"

The child presses on the *begin* button.

Robot: "*I will show you how to play the game. First, select a category from the menu below*".

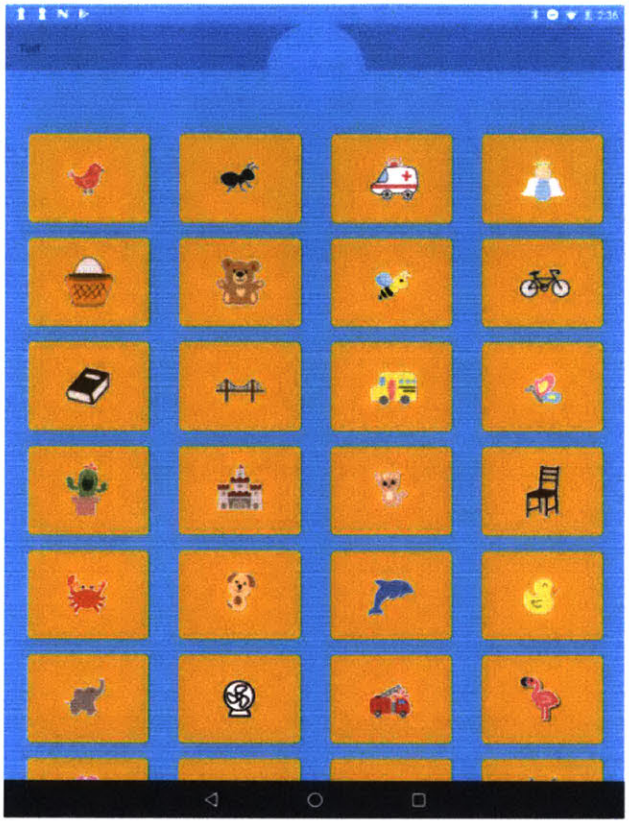
A menu drawer pops up. The child can then pull up the menu and select one of the categories [Figure 12], for example, *ant*.

Robot: "*Oh, an ant. Now draw any shape on the screen, and watch me convert it to an ant.*"

The child draws a doodle, and the robot converts it to an ant and makes multiple ant drawings. Meanwhile the child can erase and draw a new starting prompt, or can select a separate category. The robot waits for two minutes to elapse.

Robot: "*Now, it's your turn. Can you convert this doodle into an elephant?*"

The child starts drawing.



Drawing object categories supported in Magic Draw		
ANT	ELEPHANT	RABBIT
AMBULANCE	FIRETRUCK	RAIN
ANGEL	FLAMINGO	SANDWICH
BASKET	FLOWER	SHEEP
BEAR	FAN	SNAIL
BEE	FROG	SNOWFLAKE
BICYCLE	HEDGEHOG	SPEEDBOAT
BOOK	KANGAROO	SPIDER
BRIDGE	LANTERN	STEAK
BUS	LIGHTHOUSE	STRAWBERRY
BUTTERFLY	LION	SWAN
CACTUS	KEY	TIGER
CASTLE	LOBSTER	TOOTHBRUSH
CAT	OCTOPUS	TOOTHPASTE
CHAIR	PAINTBRUSH	TRACTOR
CRAB	PARROT	TRUCK
DOG	PENGUIN	WHALE
DOLPHIN	PIG	
DUCK	POOL	

Figure 12. I used Sketch-RNN and trained 55 common objects' categories from the QuickDraw dataset to generate doodle like sketches. 12.a. UI for category selection by the child. 12.b. List of 55 categories.

I observed that with this tutorial in the first round, it was easier for the child to understand the gameplay and required no human intervening. Children interacted with the game smoothly barring the occasional crashing of the tablet due to connectivity problems.

3.3.2.3. Child-Robot Co-Play

The game starts with the child drawing the prompt and selecting a category and the robot finishing the drawings. The robot waits for two minutes for the turn to switch.

Robot: *"Now, it's your turn to draw."*

The robot draws a starting prompt and selects a category for the child to draw. Every time the child completes a drawing, the participant can press on the "Done" button. A screenshot of the drawing is taken with a sound and animation feedback.

Both players play three rounds each, and then the robot terminates the game.
Robot: *"Thank you for playing with me today. I had a lot of fun making these drawings. Did you have fun?"*.

Child: *"[Yes]"*

Robot: "*I am going to go to sleep now, [child's name]. See you next time. Bye!*"

I play-tested the game with nine 6 to 9 year-old children in Somerville Public Schools as well as in a lab setting. Children reported that they found the game fun and enjoyed the co-drawing activity. Some children asked to play the game again. One child expressed frustration at the turn-switching, saying, "*It changes the turn in between my drawing, and does not let me finish. I don't like that.*" I took this feedback to incorporate a timer, so that children can see how much time they have left to finish their drawings. At the end of the game, the children can see all of their images and the robot's images and they can rate each of these images on a scale of 1 to 5. The entire gameplay lasts about 15 to 20 minutes including the gap in turn switching, selecting categories and answering the post test image rating in the app.

3.3.2.4. Robot Interactions

The robot is a fully autonomous collaborative peer that collaboratively makes drawings with the child. While the drawings are being created on the tablet screen, the robot logs information about which drawings are being drawn and when. Hence, during the time of drawing, the robot looks down upon the screen to emulate the artist. Note that in actuality, the drawings are being drawn by a model sending strokes to the tablet and not actually the robot, but the robot pretends to take the role of the drawer by looking down at the tablet and through speech prompts that suggest that he is indeed making the drawing. The robot generates dialogue while the model is generating these drawings. For instance, the robot would say, *"Oh an [ant]. I can make that drawing into an [ant]", "Look at me go"* or *"Watch me convert your doodle into a cat"*. The robot also engages the child by asking for feedback, *"What do you think about my drawings?"*, or *"Do you think that looks like an [ant]?"*. Additionally, the robot also displays the selected category icon on its face to demonstrate an association with the category chosen.

Every time the child completes a drawing and presses on the "Done" button, the robot provides feedback. The robot matches the drawing to the model category, and based on the confidence of image classification, it responds with a positive or neutral response. If the drawing has an 80% or higher match to the category, the robot responds with a positive feedback. Positive responses include, "*Good job*", "*That was a good one*", "*You are an artist*", and "*That looks so much like [an ant]*", and are accompanied by animations of joy, excitement or happiness. If the model has a match confidence of less than 80% with the category, the robot responds with a neutral feedback. Neutral responses include, "*Oh was that an ant?*", "*Let's try another one*", or "*Do you want to try making another doodle?*", and are accompanied by animations of joy, confusion, or curiosity.

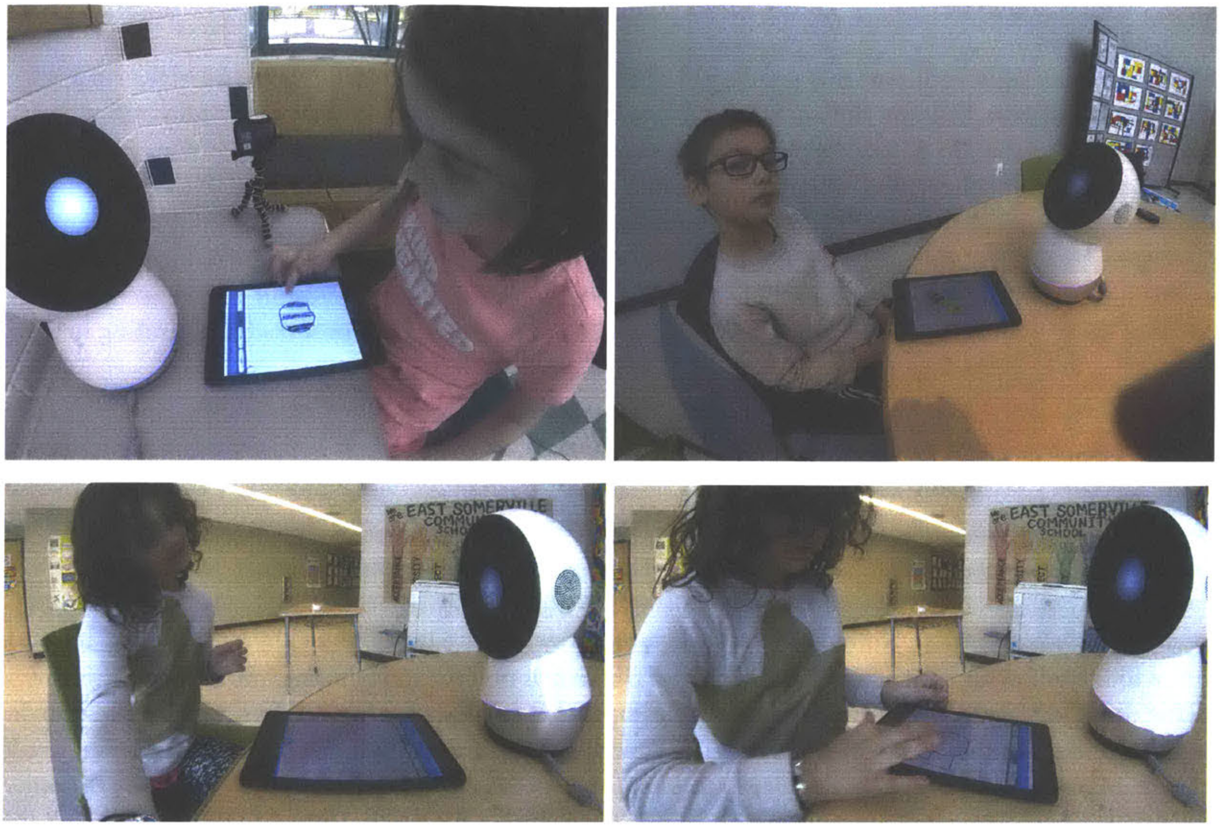
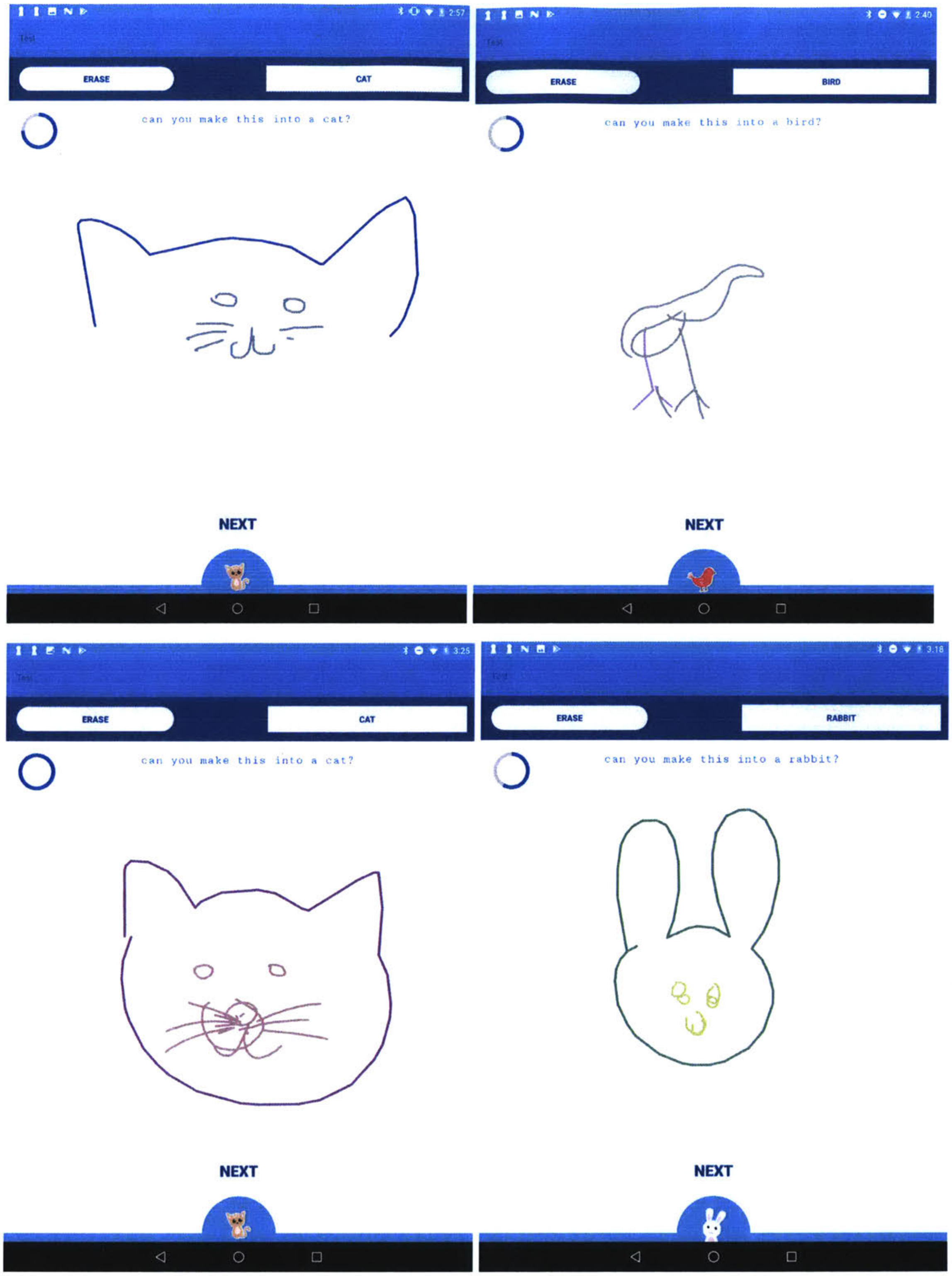


Figure 13. Children playing Magic Draw with Jibo robot



can you make this into a cat?

can you make this into a bird?

can you make this into a cat?

can you make this into a rabbit?

Figure 14. Example of drawings started by the child and completed by the robot

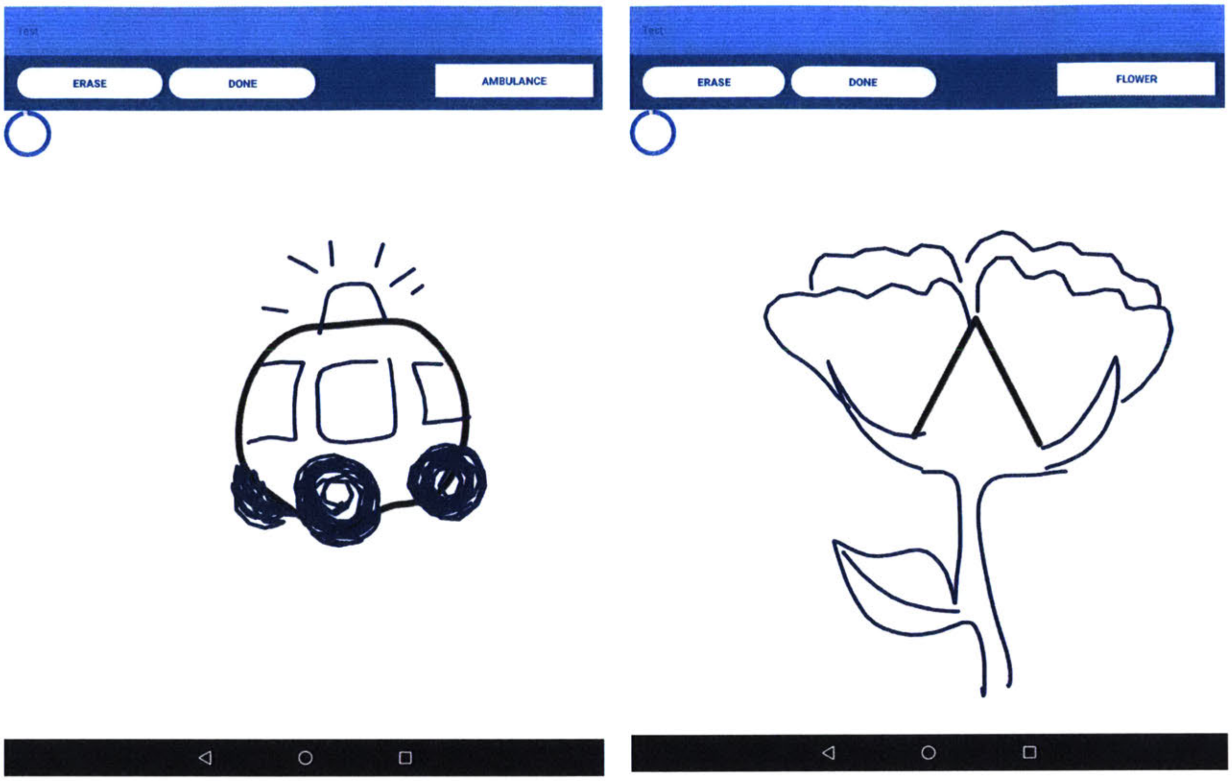


Figure 15. Examples of drawings started by the robot and completed by the child

3.4. WeDo 2.0 Construction Activity Interaction Design

A common means to foster creative learning in classrooms is through construction and maker based activities, such as making art, LEGO, DIY science toys, electronics kits, etc. In the theory of *Constructionism*, Papert [35] elaborates the importance of making in creative learning, and how people learn best when they build physical, shareable objects . The definition of creativity has evolved from being a function of the individual to an interaction between aptitude, environment, and process by which an individual produces a tangible product [63]. In order to afford creative expression through making, I incorporated a third activity that involves a LEGO based construction kit, called the LEGO WeDo 2.0 set. LEGO Education WeDo 2.0 Core Set [60] is a hands-on STEM solution that combines the LEGO brick, classroom-friendly software, engaging standards-based projects and a discovery based approach. The sets aim to introduce children to computational thinking and engineering principles in a fun and engaging way. Children use a visual programming interface on a tablet app to program the WeDo blocks.

Figure 16.a. WeDo 2.0 construction kit. 16.b. Rover using a sensor and a motor constructed using WeDo 2.0 blocks. 16.c. Visual programming interface used to program the WeDo controller.

Children's creativity is stimulated through scaffolding offered by tutors in the form of asking reflective questions, providing challenges, positive reinforcement and suggesting new directions [20,23]. Further, children learn from tutors and peers exhibiting creativity and model their behaviors. In order to understand if social robotic peers can be effective in *creativity scaffolding*, I designed a robotic interaction that involves children making construction projects using the WeDo 2.0 construction kit in the presence of a social robot that assumes the role of a tutor and offers scaffolding to the child. The robot also exhibits creative behavior itself, like generating novel ideas, and reflecting on previous actions.

Children first work towards a goal of building a rover using LEGO blocks, and programming it to avoid obstacles. This enables them to learn how to work with the WeDo blocks, and program using the Android interface. Then, they are allowed free play where they can explore different functions of the WeDo app and add different WeDo blocks. During the guided activity, the robot provides step-by-step instructions to construct and program a rover. During the free play activity, the robot offers scaffolding in the form of reflective questions, challenges, and new ideas. The robot also provides positive feedback on children's novel ideas and actions.

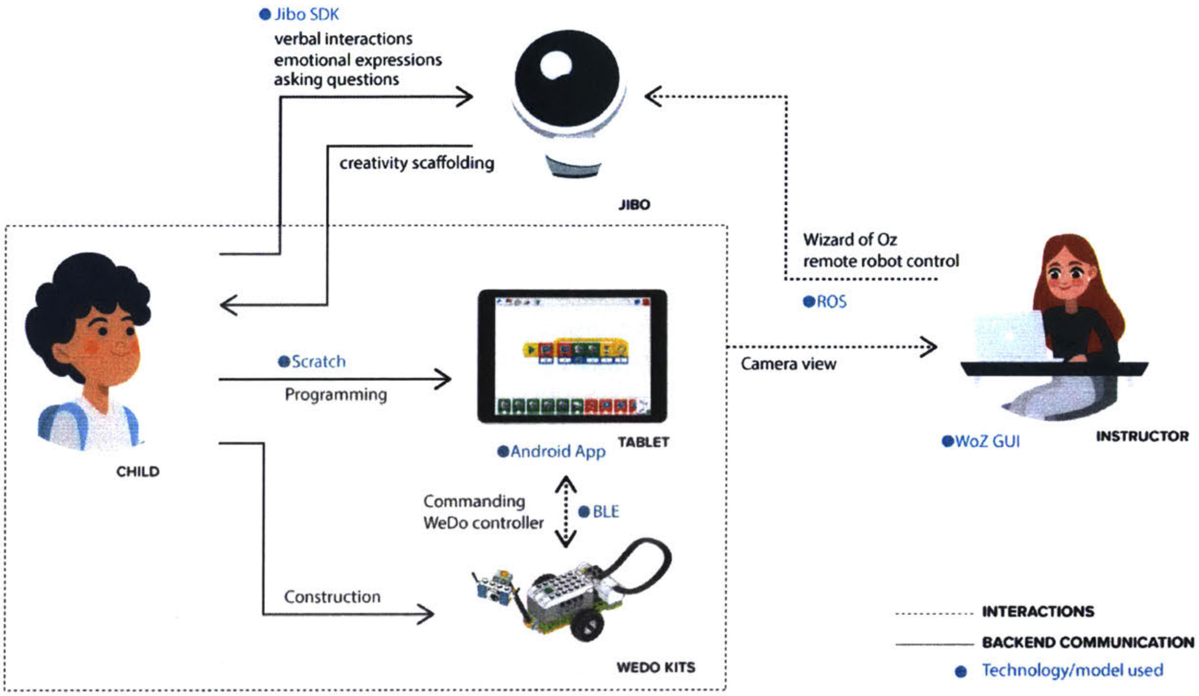


Figure 17. Model of interaction for the WeDo construction game where the robot provides *creativity scaffolding*.

The robot interaction is *Wizard of Oz*, in that it is not fully autonomous, but is controlled by a human instructor using a dynamic and predictive Graphical User Interface (GUI) on the desktop. The desktop application communicates with the robot using ROS (Robot Operating System) [77]. Children program the WeDo controllers using an Android application on a tablet screen. I developed a clone of the WeDo 2.0 Android App in order to track which UI blocks the children are using. In the sections below, I describe the construction activity, the Android app design for the programming app, the robot interactions, and the iterative GUI design process to control the robot.

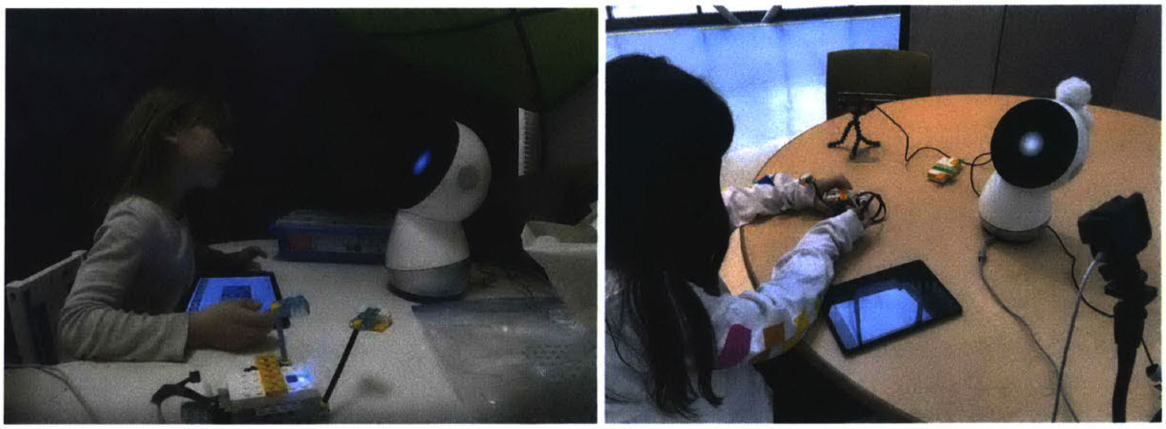


Figure 18. Children constructing models using the WeDo 2.0 construction kits while being scaffolded by the Social Robot Jibo.

3.4.1. WeDo Construction Activity Design

In this interaction, the child and the robot engage in a collaborative construction activity with a LEGO Education WeDo 2.0 [60]. Children can use all WeDo 2.0 standard construction kit [Figure 16.a.] items including a Bluetooth enabled controller, LEGO bricks, motors and supporting construction material. However, children are limited to using only one motion sensor and no tilt sensors. The activity is conducted collaboratively with Jibo who takes the role of a tutor that scaffolds the child's creative learning. Children use the WeDo kit for construction, and an Android tablet for programming the controller. The entire interaction is guided completely by the robot. The interaction begins with the robot taking children through a guided tutorial about building a rover [Figure 16.b.], that can detect obstacles and respond to them. This is an activity borrowed from the WeDo classroom project guide, and introduces children to use the WeDo controller, use motors and sensors, and program some amount of logic using a visual programming interface on the tablet. It introduces them to sequential commands, condition statements, delays, and loops. I start the interaction with this activity to ensure that all children have the basic knowhow of how to use the different modules of the WeDo construction kit. This guided activity is conducted in a step-by-step dialogue exchange between the child and the robot and lasts for six minutes.

Followed by the guided activity, children are instructed to use the kit in an open ended activity to make their own creations along with the robot. The idea generation process is guided by both the child and the robot. Throughout the interaction, children can ask the robot questions and get troubleshooting guidance. The robot also engages in active *creativity scaffolding* which involves asking the child reflective questions, challenging their ideas and assumptions, and suggesting alternate ideas. The robot also provides feedback and positive affirmation after children generate new ideas. All robot interactions for *creativity scaffolding* are outlined in the following sections.

3.4.1.1. Visual Programming App Design

Children use an Android tablet application to program the WeDo controller [Figure 19]. The WeDo programming application designed for an Android tablet is a clone of the original WeDo 2.0 application that makes use of visual programming blocks to help children program with ease. The application communicates with the WeDo controller using Bluetooth communication which enables the tablet to connect to the controller's Bluetooth Low Energy (BLE) module. I made use of a clone application instead of using the original WeDo application because I wanted to track in real time the usage of different programming blocks to have the robot respond to them. While the application can be used on any Android tablet with Android OS 6.0 and above, I made use of Google Nexus 2015 tablets with Android OS 7.1.1 in my studies.

The programming interface is a Scratch inspired visual programming interface. It makes use of a drag and drop programming environment where different draggable blocks are used for different kinds of functionality (example, actuators, or conditions). Visual programming interfaces make it simple for children to program by helping them visualize the logic [74]. In a previous workshop that I conducted at the same schools, children were given a basic introduction to using Scratch Junior [75], so all participants had familiarity with using the programming environment.

The application color codes blocks depending on their functionality - such as all motor buttons are green, but all sensors are orange. Further, I also added the feature of highlighting some blocks by drawing an outline around them. This was done so that it becomes evident what block the robot is talking about, by bringing it into focus. I made use of the MIT App Inventor BLE Extension [76] to connect with the WeDo 2.0 controller over Bluetooth. Note that App Inventor BLE extension doesn't use handles, just UUIDs. Hence, a Service UUID and a Characteristic UUID are needed for the app to use the BLE Extension.

For the rest of the application, I mirrored the functionality of the WeDo 2.0 Android application. The application also allows children to upload their own media such images and sound clips to personalize the interactions.

Drag-and-drop programming environment.

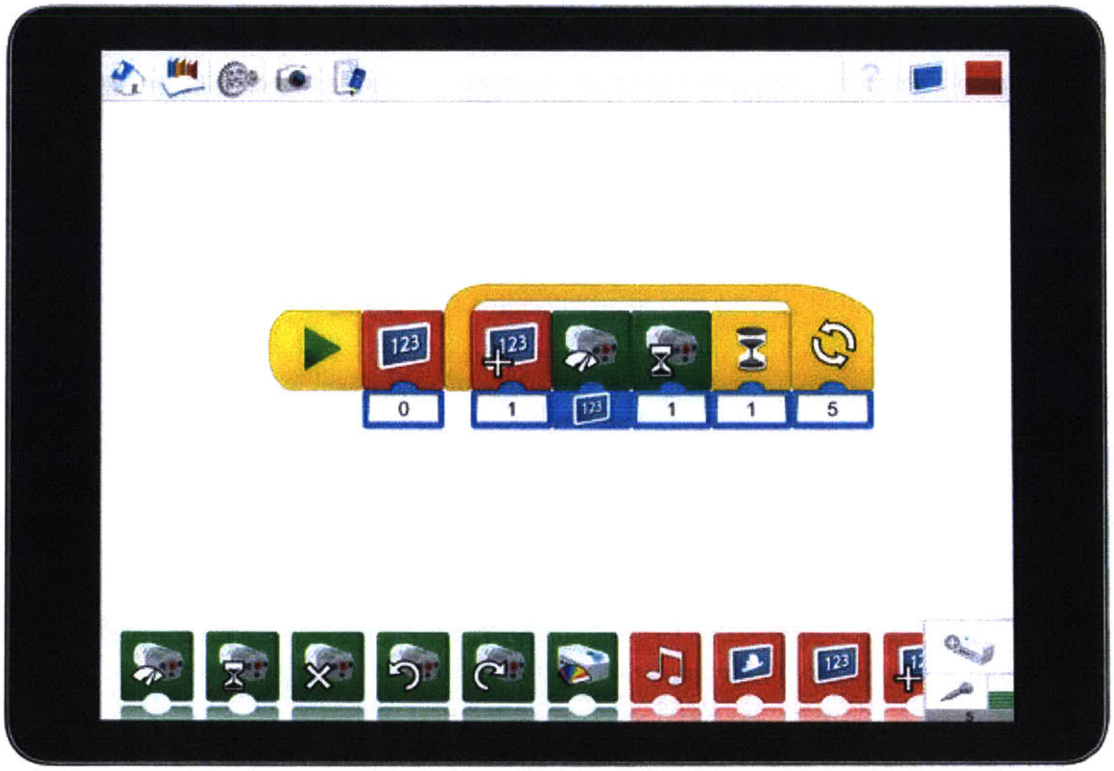


Figure 19. The WeDo 2.0 Android app interface that children use to program the WeDo controller

3.4.1.2. Robot Remote Creativity Scaffolding Interface

I use a *Wizard of Oz* way to control the Jibo robot actions for this task. I designed a robot control Graphical User Interface (GUI) for the desktop [Figure 20] that trained instructors used to control the robot. This interface is iteratively co-designed along with the instructors with the aim of assisting instructors to provide *creativity scaffolding* to the children. The control interface is designed using Python Tkinter. Tkinter is Python's de-facto standard GUI package. It is a thin object-oriented layer on top of Tcl/Tk [71]. The interface communicates with the robot using rosbridge protocol. The Jibo robot's SDK allows users to run developer skills that make Jibo to enter different *modes*. The default robot mode of Jibo is called the *Be* skill. Jibo can also enter to the *Rosbridge Receiver* skill, where ROS messages from a computer control Jibo's actions. The computer runs a *Roscore*, and Jibo communicates with the computer by running the *Rosbridge Receiver* skill on Jibo and connecting to the computer's ROS IP. I made use of the Jibo Rosbridge Receiver communication protocol developed by the Personal Robots Group at MIT Media Lab. The robot control is completely managed by the instructor from the desktop using this GUI. The iterative process of designing the GUI is outlined in the GUI design section below.

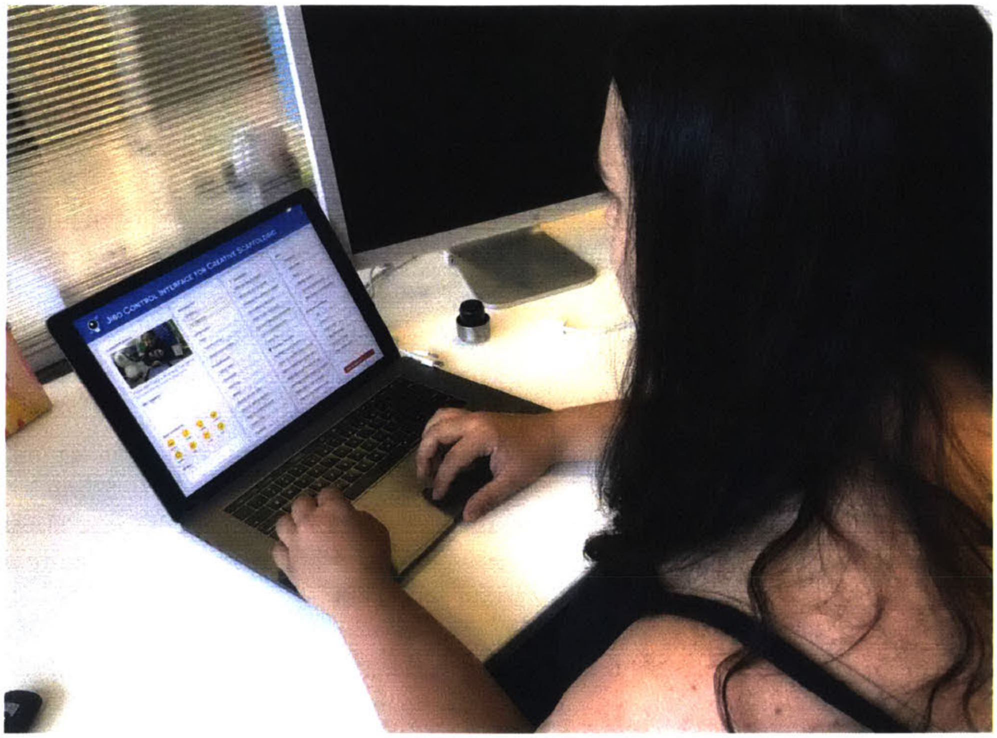


Figure 20. Instructor using the Jibo remote control GUI to control the robot.

3.4.2. Interaction Scenario

3.4.2.1. Robot Introduction

The robot Jibo guides the entire activity. Jibo looks at the child, and begins with introducing himself and doing a little ice breaker activity.

Robot: *"Hi. My name is Jibo. What is your name?"*
Child: *"Emily"*
Robot: [*affection* expression]
Robot: *"It is so nice to meet you. My favorite activity is to do my favorite dance!"*
Robot: [*dance* animation]
Robot: *What activities do you like?"*

3.4.2.3. Task Introduction

Jibo introduces the child to the activity to give them an overview of what they will be doing.
Robot: *"Today, we will be programming this rover robot to do cool things."*

Robot: [*looking down* animation]
Robot: "*Are you ready to begin?*"

The robot waits for a response. When the child says *yes*:

Robot: [*spin-head* animation, *excited* expression]
Robot: "*Let's go!*"

3.4.2.4. Child-Robot Co-Play

The robot then begins a step-by-step guided activity to help children program a rover with the LEGO WeDo kit. This is to ensure that all children have an equal understanding of using LEGO bricks, sensors and motors, and programming the WeDo controller. After this guided activity, children are free to explore and build new models with the WeDo kit. The robot provides *creativity scaffolding* to the children to help them come up with multiple novel ideas.

3.4.2.5. Robot Interactions

Jibo's role in the WeDo construction activity is to provide instructions to a. help children learn how to use the WeDo construction kit, and b. to scaffold them to be more creative while constructing models. While the tone of interaction is collaborative, for instance, Jibo says, "*Today, we will be building a rover together*", Jibo primarily takes on the role of a tutor that is helping children create. Jibo interacts with the children through speech prompts and emotional expressions. All Jibo interactions in this activity are remote controlled by a human instructor in a *Wizard of Oz* fashion.

Actions for *creativity scaffolding* are inspired from how human instructors and peers scaffold children and enable them to be more creative, such as ask reflective questions, come up with many diverse ideas, challenge assumptions, provide feedback, and appreciate the value of the children's ideas. Literature of creativity and divergent thinking elaborates how asking reflective questions, presenting challenges and positive reinforcement can foster creativity in children and adults [20, 23]. Collaboration with peers and tutors is also beneficial for creative thinking [65]. In this activity, while there are no fixed interactions that Jibo has, there is a remote control GUI that instructors use that has preset suggestions of prompts that the instructors can use, as described in the GUI design section below. These prompts are modelled from speech and emotional prompts from human instructors assisting children be more creative. I describe the design of the interface in detail in the following sections.

3.5. GUI Design for Creativity Scaffolding Interface

3.5.1. Overview

The goal of designing a robot control interface was to provide instructors with a tool to remote control Jibo that enables them to provide *creativity scaffolding* to children. I aimed to design a usable, easy and efficient interface that provides interaction presets as well as flexibility to provide instructors with maximum functionality without compromising usability. I took the approach of *learning from the wizard* [73] to design the interface. I first gave three instructors a fully flexible interface where they could freely generate dialogues and animations for Jibo, while having a birds eye view of the interaction. I then categorized these dialogues into different kinds of interactions, and provided a structured GUI for interaction where the used buttons to control Jibo, but could also type free speech if required. Based on their interactions with the interface and feedback post interaction, I iterated on the interface until I reached a level where the instructors reported the interface presets to be sufficient for their needs barring some outlier interactions. Further, based on their interactions and their correlations with the child's actions on the tablet, I developed a dynamic *predictive suggestions* feature where the interface would prompt the instructor with GUI elements to use when the child performed a certain action. These stages of GUI design for *creativity scaffolding* are described below.

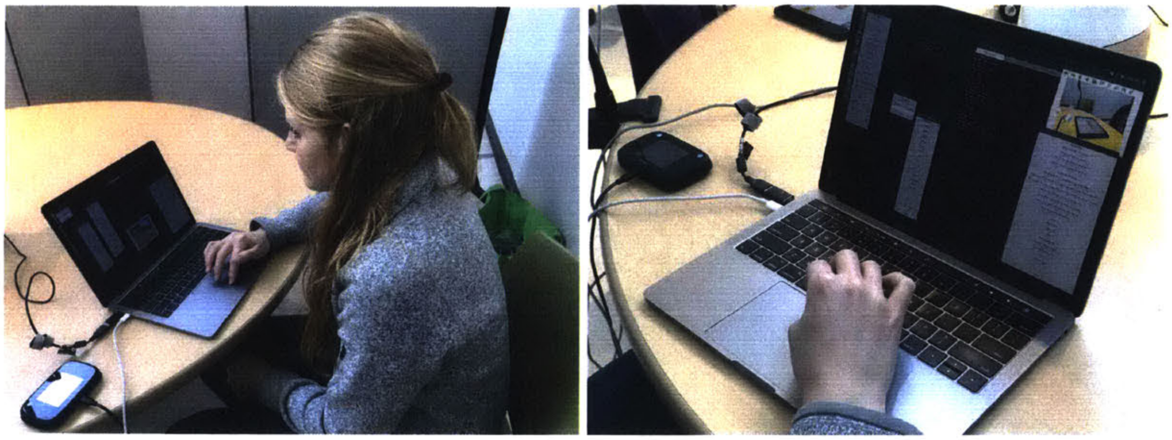
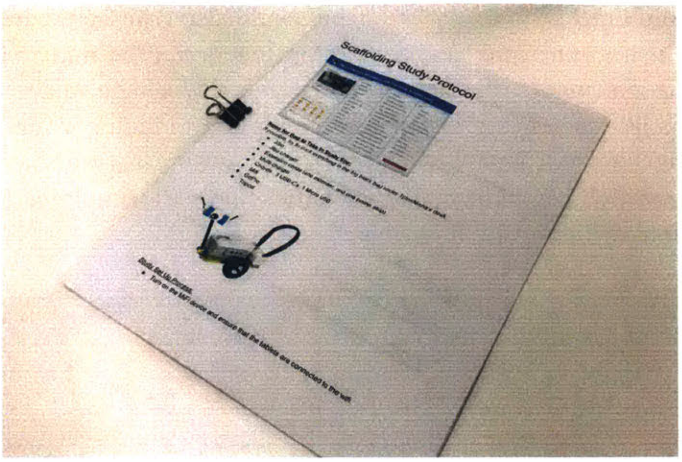


Figure 21. Instructor using the Jibo control interface for *creativity scaffolding* in the WeDo construction task

3.5.2. Iterative Design Process

3.5.2.1. Modeling instructor's instructions to a remote robot control interface

I recruited three instructors for this co-design activity. One of these instructors was from the after-school program where we recruited students from, and had 3 years of experience teaching children in elementary school. Two of these instructors were students from MIT. All instructors were trained collectively to gain an understanding of the task and the WeDo construction kits. The instructors were told that they are tasked with guiding the children to build a simple rover, and then to assist children in building other creative models. Further, all instructors were given a detailed protocol guide to use the graphical interface to control Jibo [Figure 22]. They were informed that the goal is that they help children think creatively. I designed a simple desktop based Jibo control interface which allows instructors to type free speech and use animation commands for Jibo. This interface also provided them with a bird's eye camera view of the interaction to get an idea of what the child is doing. Instructors were not blind to the study, and were told that the goal of the activity is to design a preset GUI with buttons for speech that they use frequently to make the scaffolding faster and easier for them.



Scaffolding Study Protocol

Figure 22. Scaffolding study protocol guide for instructors

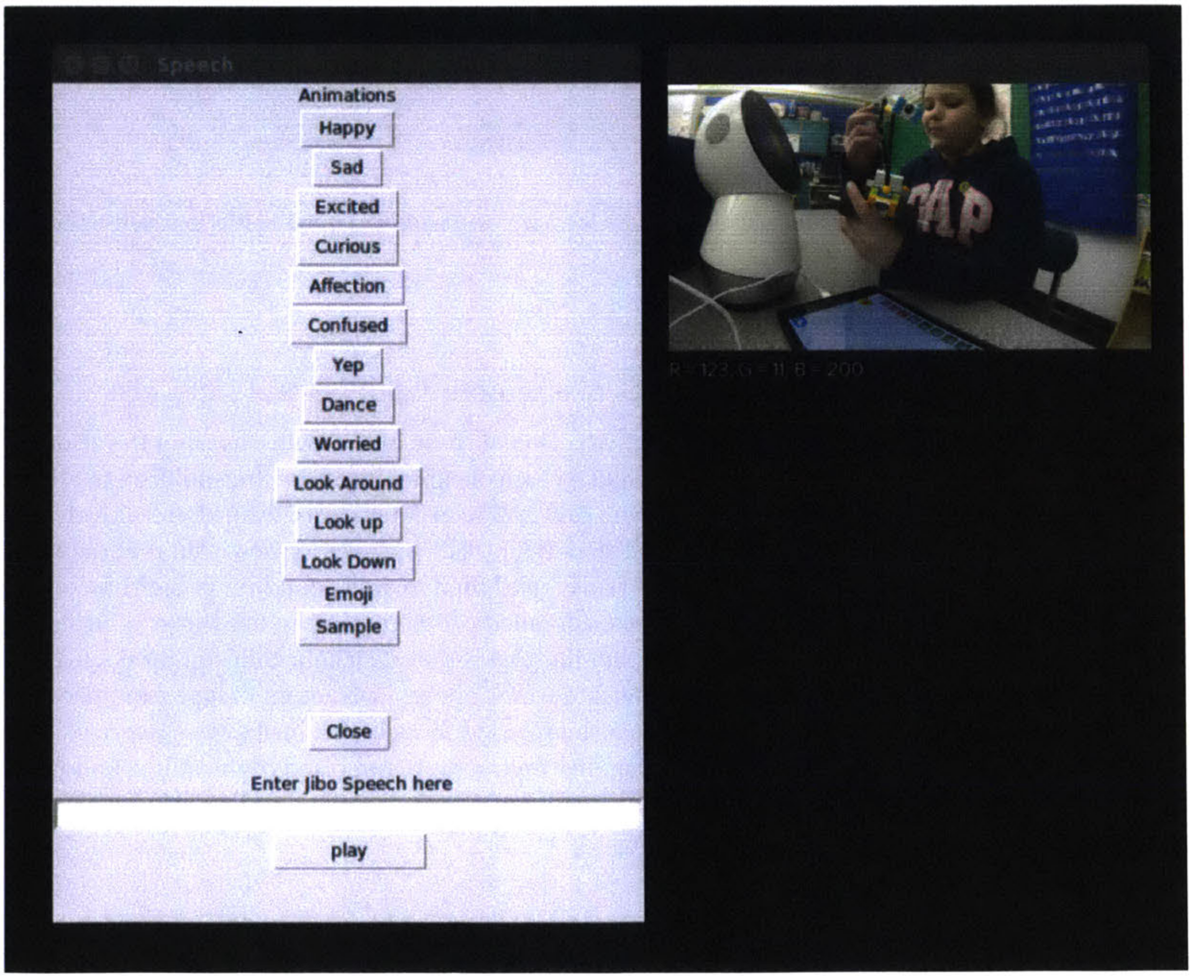
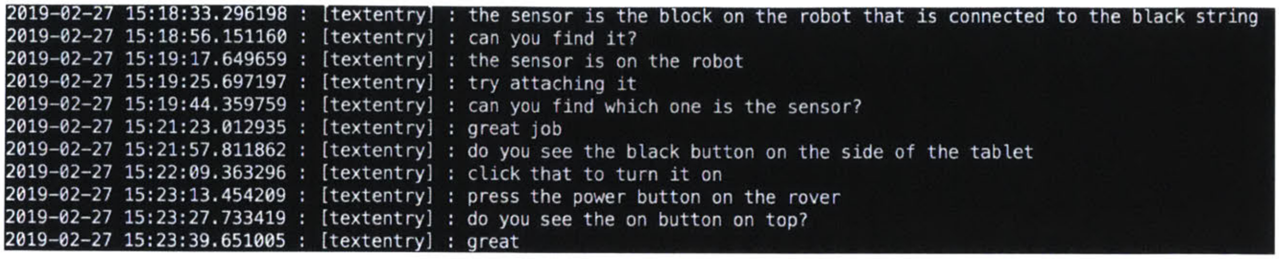


Figure 23. Version 1 of the Jibo control interface for generating Jibo speech commands and emotional expressions.

I conducted the first playtest with eight children and three instructors that used the remote control GUI. As expected, it lead to interactions with great time delays since the instructors had to type out all the commands in real time. I logged all the speech prompts that the instructor used and their timestamps of usage.



```
2019-02-27 15:18:33.296198 : [textentry] : the sensor is the block on the robot that is connected to the black string
2019-02-27 15:18:56.151160 : [textentry] : can you find it?
2019-02-27 15:19:17.649659 : [textentry] : the sensor is on the robot
2019-02-27 15:19:25.697197 : [textentry] : try attaching it
2019-02-27 15:19:44.359759 : [textentry] : can you find which one is the sensor?
2019-02-27 15:21:23.012935 : [textentry] : great job
2019-02-27 15:21:57.811862 : [textentry] : do you see the black button on the side of the tablet
2019-02-27 15:22:09.363296 : [textentry] : click that to turn it on
2019-02-27 15:23:13.454209 : [textentry] : press the power button on the rover
2019-02-27 15:23:27.733419 : [textentry] : do you see the on button on top?
2019-02-27 15:23:39.651005 : [textentry] : great
```

Figure 24. Data log of all the speech prompts that instructors used to command Jibo speech

I used an affinity diagramming method to categorize all the prompts that were used by the instructors and formed the following categories :

- Instructions : Construction and programming instructions with the goal of teaching the children how to use the WeDo construction kits and build their rover. Instructors tended to use the same language of instruction that was provided to them in the protocol.
- Questions : Reflective questions that the instructors asked the children. For example, '*Can you tell me why you did that (last action)?*" or "*How will you do that?*"
- Creativity prompts : All prompts that were not direct instructions to the children but were focused towards helping children coming up with creative ideas. These included new ideas and challenges.
- Feedback : All responses to children's actions. These were mostly positive feedback, such as, '*Good job*', but also involved encouragement prompts such as '*Let's try again*'.
- Frequently asked questions (FAQ): There were some times when children asked the robot questions to help them troubleshoot problems. I observed some patterns of problems such as connection to Bluetooth, or not being able to find a part. I first clubbed the responses under topic such as '*Bluetooth*', or '*Missing part*' and then clubbed all of the instructors' responses to these questions were clubbed under FAQ.

In order to save the instructors' time involved in typing out each speech prompt, I designed a very simplistic Python GUI on the Desktop with these preset phrases that the instructors frequently used. I incorporated every phrase that was used 3 or more times (or can be clubbed with very similar phrases).

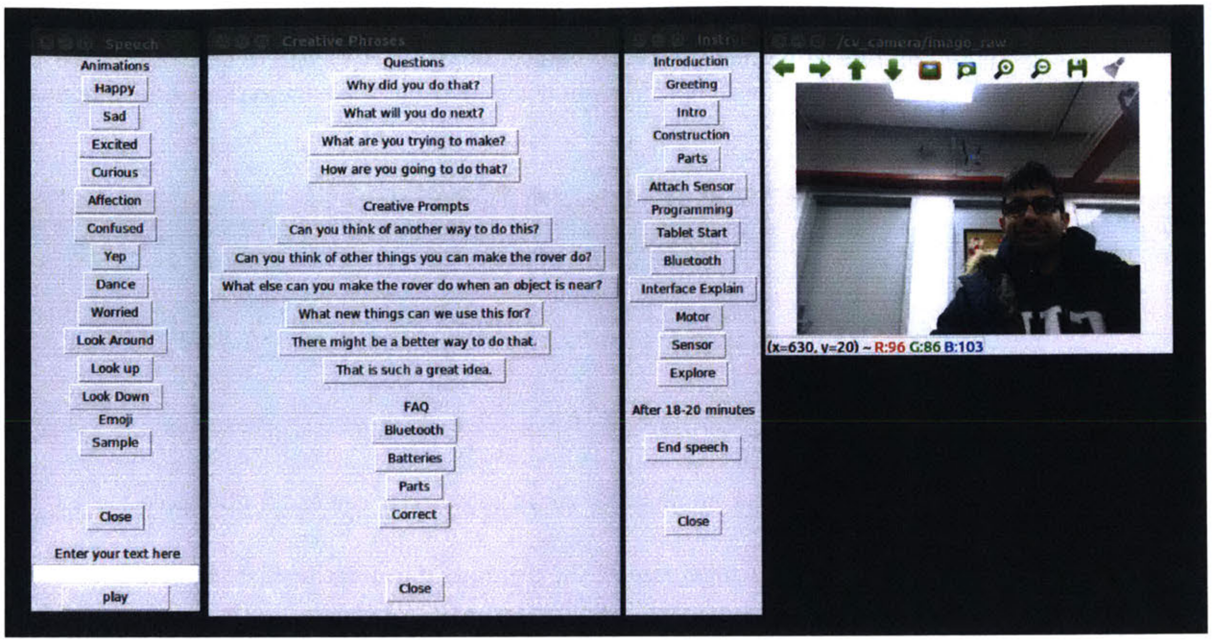


Figure 25. Version 2 of the Jibo control interface for *creativity scaffolding*

3.5.2.2. Testing and iterating on interface

I then evaluated this interface with the three instructors by using a Think Aloud method of evaluation [78]. I asked the instructors to perform the same scaffolding task using the interface, while a colleague acted as the participant performing the construction activity. I had the instructors think aloud during the interactions about what actions they want to perform, how they use the interface to perform it, and what the interface does not allow them to do. At the end of the interaction, I asked them the following three questions :

- What worked in the interface to help you give instructions and scaffold for creativity?
- What did not work in the interface?
- Were there parts of the interface that you did not understand the functionality of?
- What will you change in the interface to better suit your needs.

I then conducted a paper prototyping session with them where they presented their design ideas about designing a better control interface.

The main insights that I received from this co-design session were the following :

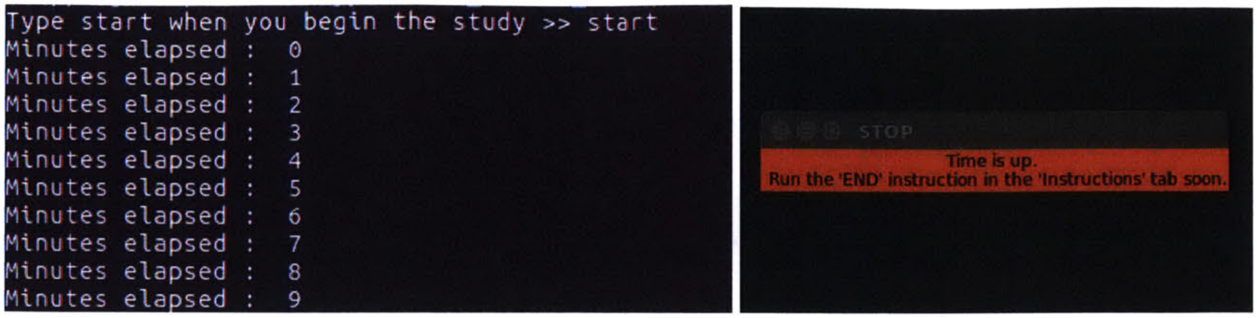
- Categorization : Instructors liked the categorization of prompts in *questions, creative prompts, instructions,* and *FAQs*. One instructor said, "*The organization helped me easily find the prompts and I liked that the instructions were in order of construction*".
- Easy to use : Instructors also appreciated the no-frills easy to use interface.
- Short labels : Instructors thought that the interface was too overwhelming and it did not really need the complete sentences of each prompt. They suggested that proving keywords and perhaps some visuals would be helpful.
- Break down instructions : Instructors suggested that some longer instructions such as *'Sensors'* are actually 3 different instructions and should be broken down into multiple prompts. This saves

them from typing out a specific part of the prompt that the child is having trouble with. Hence, I broke the instructions down into smaller segments (such as three instructions for attaching the sensor, using the sensor block, and testing the sensor).

- Miscellaneous frequent phrases : There were other conversation snippets, typically used as responses, such as, '*Yes, that is correct*', or '*I don't know*' that I clubbed under *Frequently used phrases*.
- Further, I added and removed some prompts based on instructors' feedback and frequency of use.

After incorporating these design changes, I had a second version of the interface which I tested in the schools. I conducted user studies with the instructors using the interface with nine children in the target age group. While I could not do think alouds since the interface was actively being used by the instructors to scaffold children, I conducted post test interviews to get their feedback and design ideas about improving the interfaces. The main insights I received from this feedback session were the following :

- Instructors suggested that sometimes they wish to enter the same command multiple times and it is cumbersome to repeatedly type the same thing. I also observed that they were copy pasting the commands repeatedly. Hence, I made the speech box have memory of the previous command, and display it, so they could just repeat it.
- Instructors also mentioned that there is often the need to stop a command midway and make Jibo say a new thing, which is easy to do in natural conversation. But the Jibo controller did not allow this, since it would fully complete one command message that was sent over ROS before initiating another. I was initially disabling all UI buttons while Jibo performs any action which was limiting the instructors from initiating a new command. To tackle this, I enabled the buttons added a mechanism that allows instructors to initiate a command in between another ongoing Jibo interaction. All new commands automatically stop the previous command and initiate new Jibo speech, which resembles Jibo interrupting himself and initiating a new speech. In order to make this a more natural interaction, Jibo must say a filler word such as *'umm'*, before starting the new prompt. While this was not incorporated in the current version of robot speech, I plan to do that in the future.
- Instructors mentioned that it would be helpful to have an idea of how much time has elapsed so they don't have to manually keep time and stop the interaction. Hence, I added timer as well as a console print of the number of minutes elapsed. Further, I added an automatic pop-up after 20 minutes have elapsed to notify the instructor that the interaction must stop [Figure 26]. Though the system does not automatically stop the interaction, and the *end speech* command's timing is still at the discretion of the instructor in order to not interrupt the child in case they were in between an action.
- Lastly, instructors mentioned that they have a lot of thoughts about the interface's usability during the interaction that they would like to report, as well as make notes about occurrences during the interaction, such as, if they restarted the interaction. For this need, I made a text box that instructors could add notes in and it would log the notes with a timestamp.



```
Type start when you begin the study >> start
Minutes elapsed :  0
Minutes elapsed :  1
Minutes elapsed :  2
Minutes elapsed :  3
Minutes elapsed :  4
Minutes elapsed :  5
Minutes elapsed :  6
Minutes elapsed :  7
Minutes elapsed :  8
Minutes elapsed :  9
```

Time is up.
Run the 'END' instruction in the 'Instructions' tab soon.

Figure 26. Instructors can see a time elapsed update print on the Desktop's terminal. A pop-up notifies the instructor after 20 minutes have elapsed, prompting them to run the *End speech* command.

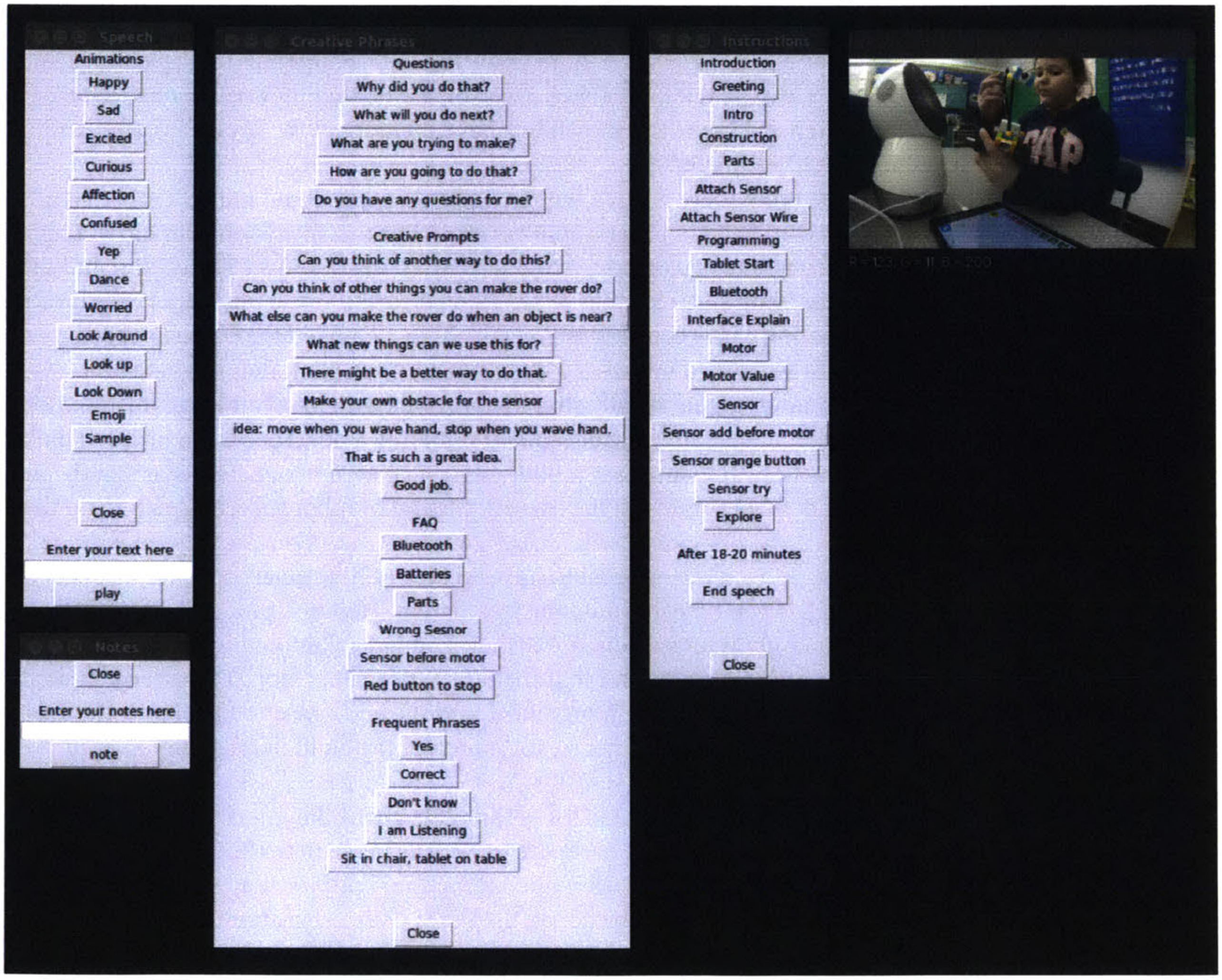


Figure 27. Version 3 of the Jibo control interface for *creativity scaffolding* during the WeDo construction task.

I designed a third version of the control interface [Figure 27], which included all these design changes. Further, I also incorporated some interface design principles such as aligning and color coding to make the interface more intuitive and aesthetically pleasing [Figure 28]. I also displayed the child speech as recognized by Google's Automatic Speech Recognition (ASR) model on the interface, below the video feed. Instructors still had a live audio and video access to the scene, but the ASR text was there to aid them with understanding what the child said, and for us to collect child speech data. It is important to note that instructors reported that the ASR was not very accurate. Jibo speech was still controlled by typed out speech commands by the instructor. In future versions of this interface, it could also be helpful that instead of typing out speech commands we make use of ASR to use instructors' speech as input to the robot.

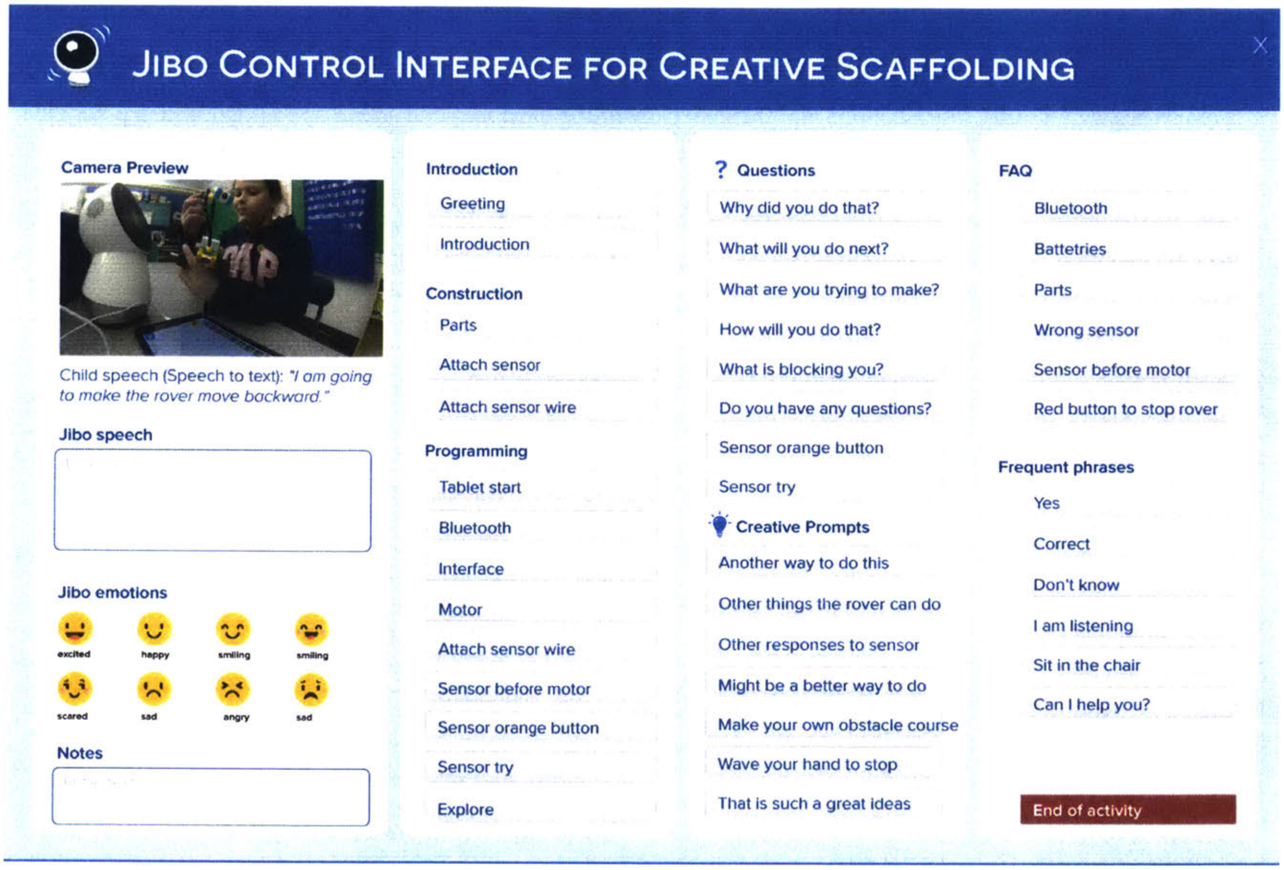

Child speech (Speech to text): *"I am going to make the rover move backward."*

Figure 28. Version 4 of the Jibo control interface incorporating interface design for usability and aesthetics

3.5.2.3. Interactive Interface with suggestions

Lastly, I logged all instructor interactions with the GUI through 20 playtests and coded them with the following :

- Child's action leading to the interaction. For example, instructors chose the sensor FAQ after the child connected the motors, or instructor used the creative prompt after the child had the preliminary rover all built.
- Previous interaction with the interface. For example, instructor provided the 'testing sensor' instruction after the 'connecting sensor' instruction.

I looked at both tablet logs with timestamps, as well as video recording of the interaction to code these. Some examples of these codes are demonstrated in table 2.

GUI Interaction	Previous Child Action	Previous GUI Interaction
Robot Introduction Speech	Beginning of interaction	-
I1 (instruction)	Start activity	Robot Introduction speech
C2 (creative prompt)	Test rover sensor to initialize motor	C1 (creative prompt)
F1 (FAQ)	Struggle with Bluetooth connection	Q2 (question)
Q2 (question)	Using image block	C1 (creative prompt)

Table 2. Examples of GUI interactions and their corresponding previous child action and previous instructor GUI interaction

Based on this data, I calculated the GUI interaction probability following each child action [Table 3] and following each GUI interaction [Table 4]. These probabilities were calculated from data collected from 19 studies, since one study was terminated prematurely and did not record complete data.

Child action	Following GUI Interactions	Description	Probability
Connect sensor to the rover body	I9	Instruction : try out the sensor by waving your hand	0.58
	F4	FAQ : wrong sensor used	0.21
	I8	Instruction : connect sensor to rover body	0.11
	I10	Instruction : explore	0.05
	C1	Creative prompt : What else can you make the rover do?	0.05
Bluetooth connector block	F1	FAQ : Bluetooth	0.74
	Fr3	Frequent phrases : Don't know	0.16

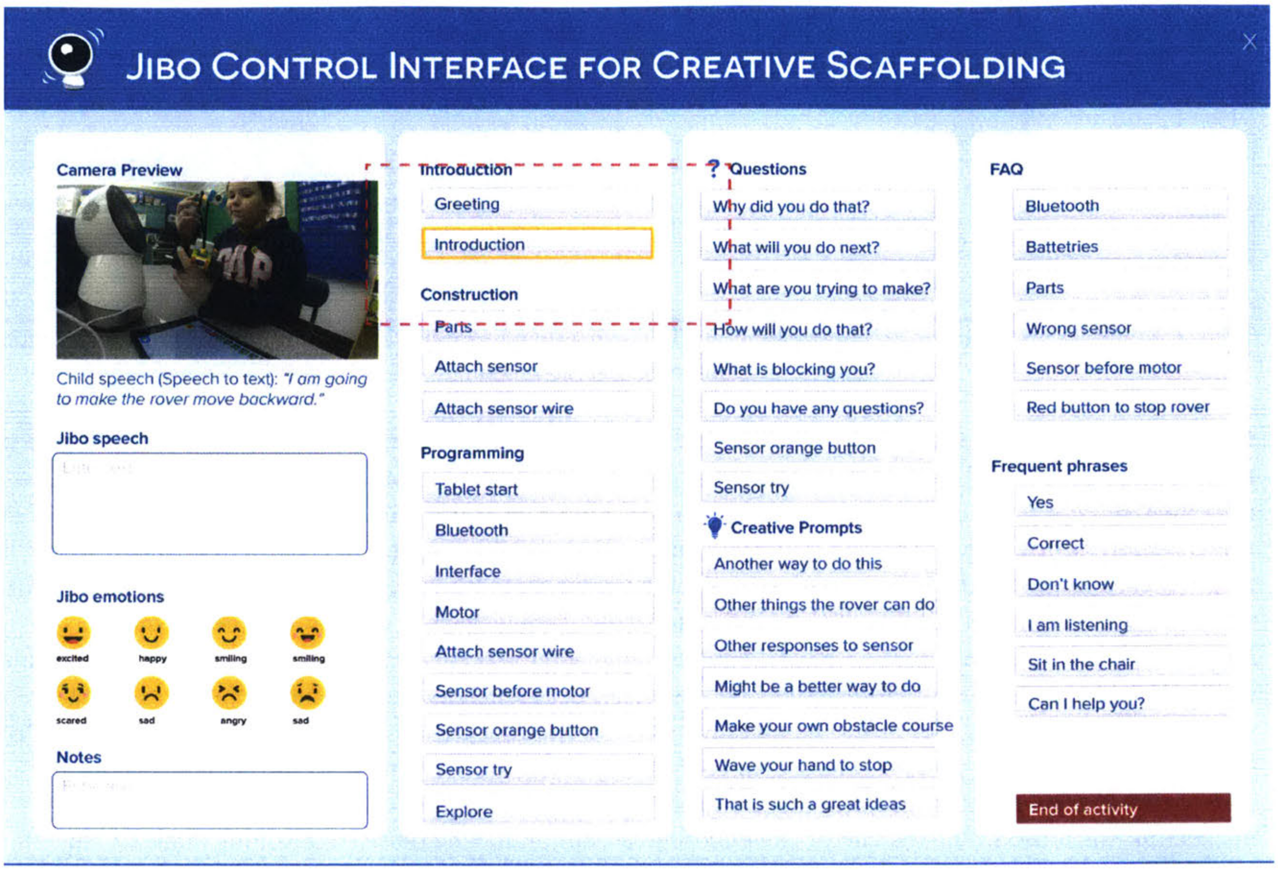
Table 3. Examples of child actions and their corresponding following instructor GUI interactions with a probability of that interaction.

GUI Interaction	Following GUI Interactions	Description	Probability
Greeting : Robot introduction and greeting	I1	Instruction 1 : introduce the activity to the child and the goal of the construction task	0.95

	I0	Greeting : Robot introduction and greeting	0.05
I10 : Instruction to explore	C1	Creative prompt : What else can you make the rover do?	0.53
	F3	FAQ : More parts	0.21
	Fr2	Frequent phrases : Correct	0.11

Table 4. Examples of instructor GUI interactions and their corresponding following instructor GUI interactions with a probability of that interaction.

I used these probabilities to predict what the instructor's next interaction with the GUI would be, based on the child's actions and based on the instructor's previous GUI interaction. For instance, if the instructor uses the *Greeting* function on the GUI, there is a very high probability that the next click would be the *Introduction* button. I used this prediction to build a dynamic suggestion interaction in the GUI, where it would highlight the predicted next action on the GUI using a glow box, which is essentially the action with the highest following probability. This highlighting would bring the next probable action to the instructor's attention, thus making the GUI interaction faster and easier for them to use [Figure 29]. This was, however, not doable for child actions on physical blocks (such as connecting a sensor), since there was no way to track it in real time. I could only model scaffolding GUI predictions for actions that children performed on the tablet and preceding actions that the instructor performed on the GUI. However, the system would send robot commands automatically, and the final robot action would still be at the instructors' discretion. The instructor can choose to accept or decline these suggestions made by the interface.



Child speech (Speech to text): *"I am going to make the rover move backward."*

Figure 29. Version 5 of the Jibo control interface incorporating interface design which incorporates predictive suggestions based on child actions and previous GUI interactions

This suggestion model also dynamically updated itself as I conducted more playtests, and as probabilities of interactions following child actions and GUI interactions changed. I was personally very interested in building this predictive scaffolding model since it paves the way to develop a fully autonomous robot scaffolding system in the context of one activity. Over time and over several playtests, the model can also reinforce itself depending on if the instructor accepts and rejects its suggestions, eventually leading to minimal error rates. This also lays down evidence that this scaffolding paradigm can be built in the context of any such activity which involves an exhaustive list of actions and materials. The replication of human instructors' scaffolding into an artificial agent, and the *learning from a teacher* model, can be beneficial for personalized assistance when the teacher is not present or when there are many students for one teacher.

It is, however, important to be wary of the shortcomings of such a suggestion based system for instructors. While these recommendations make it easy for instructors to provide help and scaffold children's creative learning, they also inhibit the instructor's original thought and manner of scaffolding, which is very valuable. In the ideal scenario, this model should be built based on data collected from several instructors with a diverse set of backgrounds and expertise, while they instructed several students with a diverse set of backgrounds. Further, the model should be able to personalize, that is, adapt itself based on one instructor's usage and allow enough space for original thought. While the current interface does allow instructors to reject the model's recommendation and also generate new Jibo speech text, it can still lead to influencing the instructors' decision making process, and have them conform to commonly used instructions, which may be counterintuitive to promoting creativity.

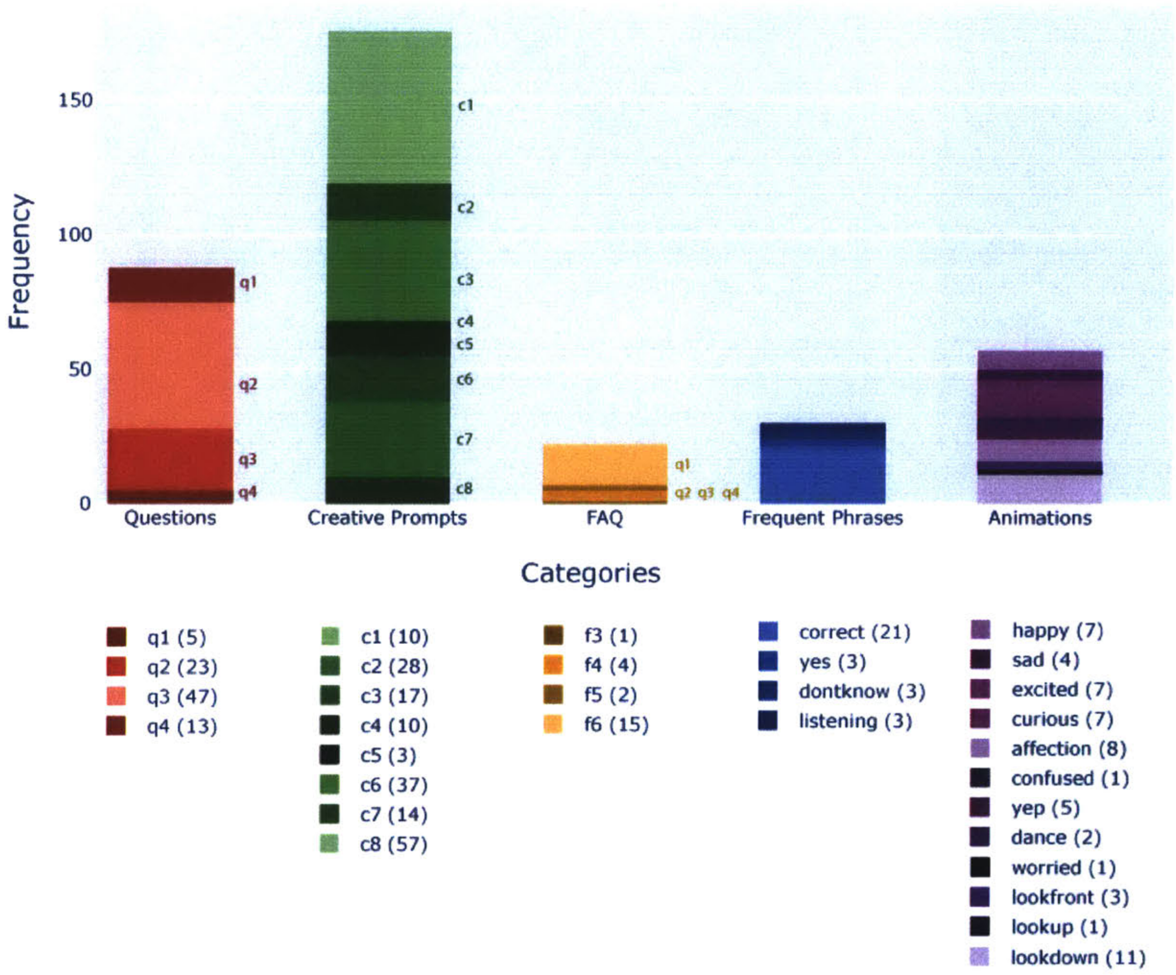


Figure 30. Instructors' log summary from 20 playtests. I iteratively redesigned the interface to add or remove prompts based on instructors' usage summary. This log helped build a predictive model for recommendations.

Questions	**Creative Prompts**	**Positive Reinforcement**
Can you tell me why you did that?	Can you think of another way to do that?	That is such a great idea! Good job.
What will you be doing next?	What are some other things you can make the rover do?	You think of some really cool use of the robot.
What are you trying to make?	What else can you make the rover do when an object is near? Can you make it have a different output?	Well done. That was so creative.
How are you going to do that?	What are some other uses for the [motor/sensor]?	Great job!
What are the materials you would be needing for that?	Let's think of some fun uses of the rover.	You are doing so well.
Do you have any questions about this?	There might be a better way to program that.	I would not have thought of that. Good going.
Is that the best way to do that?	I have an idea!	
	Let's try to make an obstacle for the rover's sensor to detect. You can use LEGO blocks to make an obstacle.	
	Let's try to make the rover move when you wave your hand in front of the sensor, and stop when you wave your hand again?	

Table 5. *Creativity scaffolding* prompts used in the Jibo remote control GUI

3.6. Escape Adventure Activity Design

Divergent thinking is the thought process of generating several and unusual ideas, typically to solve a problem. Divergent thinking is an indicator of original thought and creative potential. Runco and Acar postulated how divergent thinking can be an indicator for creativity. Divergent thinking tests are often used for creativity measurement [99]. These tests involve creative problem solving by generating 'out of the box' or atypical ideas. The fourth child-robot game interaction I designed was to foster divergent thinking in children while designing a contraption for a digital platform game.

3.6.1. Game Design

The gameplay involves a virtual game agent, that resembles the Jibo robot, in a digital game, that is trying to escape a virtual room and obeys the laws of physics [Figure 31]. Children are tasked with using objects (such as ladders, catapults, etc.) to design a contraption that helps the virtual game agent escape the room. The objects can be used in several different ways, some of which are atypical novel ways. This task is performed in the presence of the embodied agent that offers *creativity scaffolding* to the child in the form of questions, challenges and ideas. The goal of the interaction is to understand how this social robot offering *creativity scaffolding* to the child during gameplay influences their divergent thinking.

The game involves three levels with different child-friendly themes:

1. The Alien spaceship level : Jibo is stuck on an alien spaceship! Help him escape by using objects from his toolbox to jump and climb on! And watch out for the aliens on patrol. You can physically interact and transform all objects.
2. The Carnival level : Jibo is lost in a carnival. Help him reach all the balloons by objects that he can connect, manipulate, and powerup.
3. The Messy Kitchen level : Jibo is trying to make a meal. Help him make a yummy meal by unlocking ingredients and using cooking tools. You can transform objects, power them up, unlock them, connect them and manipulate them.

The main player of the game is the virtual Jibo, but the children can manipulate the game space and interact with different object classes to set up a physics contraption that helps Jibo get to the goal (like reach a flag or a balloon). Following are the object classes that the players can use, categorized by the type of interaction:

- Physical interaction: An object that players can drag into the world, and upon doing so, these objects become interactive to Jibo. Each object, however, only has one intended function. These include ladders, trampolines, boxes, ramps, slides, air poofs, pulleys, ropes, catapult, and friction mats.
- Throwable interaction: An object that players can drag into the world and give to Jibo to throw or shoot, or drop. The include balls, knives, boomerangs, horseshoes and lassos.
- Machinery tools : An object that players can use to manipulate machinery such as on/off switches, wrenches, pins, screwdrivers, pulleys, wheels and plugs.
- Connective interaction: An object that players can drag into the world, but will only work upon being connected to other objects in some fashion. These include platforms, ropes, fans, beakers, lightbulbs, wires and magnets.

The gameplay involves the child setting up the game scene using these objects, and the virtual agent tries to traverse the game space to reach the goal. The game obeys laws of physics and the agent either succeeds in making it to the goal, or falls and ends the game.

Figure 31. Escape Adventure Game levels

3.6.2. Interaction Scenario - Creativity Scaffolding

Children enable the virtual robot player to traverse the game scene in the presence of a physical robot that acts as a peer and offers *creativity scaffolding* in the form of verbal and non-verbal interactions. From the theories of creativity, we learn which social interactions and behaviors affect creativity learning. Below, I suggest some verbal and non-verbal robot interaction patterns that facilitate creativity.

3.6.2.1. Verbal behaviors

The robot engages in the following verbal behaviors to foster divergent thinking in children :

- Defining creative space :
    - "Your task is to find creative ways to teach the robot how to play the game."
- Reflection :
    - "Can you tell me why you did that?"
    - "Can you recount how you taught the robot the last time?"
- Recounting similar experiences :
    - "Maybe you can make use of a strategy you used for other objects."
- Question asking :
    - "Can you tell why you did that?"
    - "Which of these tools can you use to tackle the monsters?"
- Forming an inventory of ideas :
    - "Let's see. We know that we can duck, we can jump, and we can shoot. Do you think there is something else we can do?"
- Pushing the limits :
    - "Let's think of some more alternatives."
    - "Do you think there might be another way to do that?"
- Consider alternatives
    - "What could be some other ways to do this?"
    - "Is the other way actually better?"
    - "Is that the only way to do this?"
    - "Do you think there might be other uses for that power?"
- Build on foundational work

    - “Everyone takes the straight line approach, but some people think about rebound.”
    - “We know that we can add a condition here, but can we do something else too?”
- Validate decision, or provide positive feedback
    - “I agree, that’s a great idea.”
    - “That is such a novel idea.”
    - “Oh that was so innovative.”
- Engage in creative conflict
    - “I wonder if there is a better way to do it?”
    - “I wonder if that is the only way to do it?”
- Non-analytical / judgemental interaction
    - “I will try this silly idea, because I am a robot”
    - “Let’s not think about the points.”
    - “I have a crazy idea. It may or may not work, but it’s worth a try!”

3.6.2.2. Non-verbal behaviors :

The robot also engages in non-verbal behaviors to support the scaffolding process :

- Reflection :
    - Curious expressions
    - Uncertainty
    - Questioning
- Recounting similar experiences :
    - Thinking expressions
- Question asking :
    - Curious expressions
    - Uncertainty
    - Questioning
- Pushing the limits :
    - Excitement
    - Surprise
- Consider alternatives
    - Thinking
- Validate decision, or provide positive feedback
    - Excitement
    - Proud expressions
    - Positive affect
- Engage in creative conflict
    - Questioning
    - Critical expressions
- Demonstrating affinity and showing interest
    - Leaning in
    - Nodding
- Induce positive affect
    - Excitement
    - Proud
    - Happiness

- Avoiding negative affect emotions wherever possible

Additionally, the robot engaged in non-verbal behaviors such as leaning in and taking an interest in what the child is doing, and nodding while validating children's ideas.

3.6.3. Data collection

In order to analyze children's creativity, I make use of their gameplay behavior data. For this purpose, I collect a log of all game actions (all manipulations and actions), their speech data, and their front face video data. While gameplay helps us understand their actions, speech and video information helps us understand their expressed thought process and affect during play.

3.6.4. Evaluation of creativity in Escape Adventure

I evaluate how the robot's behavior influences participants' ability to come up with novel ideas, and creatively solve problems. In the context of this activity, creative problem solving is classified by:

1. Fluency of ideas :
    a. For every problem being solved, how many ideas did the child generate?
2. Originality :
    a. Did the child use strategies that were not a part of the tutorial?
    b. Did the child choose an alternative strategy, or a typical strategy to solve a problem?
    c. Is the child's idea deviating from the participant group's popular ideas?
3. Flexibility of ideas :
    a. What is the theme variation within the set of ideas that the child generated?
4. Value of ideas :
    a. For every new game action : How many game points did the game action lead to?
5. Debugging :
    a. For every unsuccessful idea, how many times did the child iterate to find a new strategy?
    b. For every successful idea, how many times did the child iterate to find a new strategy?
6. Recognition of hidden patterns :
    The game has implicit underlying patterns not explicitly described to the child, for instance, all machineries only use metal tools, or all monsters are followed by ammunition.
    a. How many underlying implicit connections is the child able to recognize?

Fluency of ideas	**Originality**	**Flexibility of ideas**	**Value**	**Debugging**	**Pattern Recognition**
Total number of ideas	Alternate strategy (y/n)	Theme variation	Points	Iterations for unsuccessful	Number of patterns
	Deviation from set			Iterations for successful	

Table 6. Assessment metrics for creativity in the Escape Adventure game

Note : I designed this game interaction, but did not playtest it given the time constraints and recruitment periods of students. Hence, this interaction is not included in investigations, but is referenced in the future work section.

In this **Chapter 3**, I described the design process of child-robot interactions that I hypothesize can foster creativity in children. In **Chapter 4** and **Chapter 5**, I outline my efforts to validate this hypothesis. I ran comparison studies with children, where one group of children interacted with the robot that incorporates these creativity-inducing behavior and the other group of children interacted with the robot that does not. In the following chapters, I describe these investigations and the results that I found in these comparisons. In the first investigation, I evaluate whether children model a social robot's expression of creativity in verbal and figural creativity games. In the second investigation, I evaluate whether a robot offering *creativity scaffolding* helps foster creativity in children.

Chapter 4 : Investigation I : Do Children Socially Emulate a Social Robot's Creativity?

As described in **Chapter 3**, I designed two game-based child-robot interactions where the robot Jibo exhibits different types of creativity:

1. Droodle Game Interaction : The child and the robot take turns to come up with creative titles for abstract Droodles displayed on a tablet. Players exhibit *verbal* creativity.
2. Magic Draw Game Interaction : The child and the robot collaboratively make drawings on a tablet screen. Players exhibit *figural* creativity.

I hypothesized that, in these interactions, children could emulate creativity from a social robot. Further, I hypothesized that the robot's embodiment could have a positive effect on children's creativity. In order to test my hypotheses, I ran two randomized controlled trials where with participants in the 6 - 10 year old age group. In both studies, children were divided into three groups, counterbalanced by age, gender and creativity scores as measured by the TTCT verbal and figural tests :

- Creative robot group (R_C+) : This group interacted with the robot exhibiting creative behaviors.
- Non-creative robot group (R_C-) : This group interacted with the robot that did not exhibit creative behaviors.
- Non-creative tablet-only group (T_C-) : This group played the same games in the absence of a robot, only with a tablet, where the tablet did not exhibit *creativity scaffolding* behaviors.

I investigated this hypothesis in the context of *verbal* creativity, through the Droodle Creativity game and in the context of *figural* creativity, through the Magic Draw game. In this chapter, I outline the study design and results of both these studies, while focusing on the difference of creativity gains between the three study groups.

4.1. Verbal Creativity with Droodle Game

4.1.1. Overview

In order to investigate whether children model a social robot's verbal creativity, I employed the Droodle Creativity Game, inspired from the Droodle Creativity Task, which is a verbal creativity task that draws upon people's ability to use language in witty and creative ways (Droodle titles) to describe an abstract image or figure (Droodle) [24]. I designed a game-like Child-Robot Interaction where the robot and the child take turns to generate Droodle titles. I recruited 51 participants in the 6-10 year old age group that played 5 rounds of the Droodle Creativity Game with Jibo. Participants were divided in two balanced groups based on their pre-test creativity measures (as measured by the standardized Torrance Test of Creative Thinking test), age and gender. One group interacted with the robot that exhibits creative behaviors (R_C+), that is, chooses more number of ideas, chooses unique ideas, and chooses creative ideas from a library of pre-generated ideas. The creative robot also engages in non-verbal interactions such as curiosity for new ideas and joy when it generates an idea. The other group interacts with the robot that exhibits non-creative behaviors (R_C-), that is, chooses less number of ideas, chooses less unique ideas, and chooses less creative ideas. In order to understand the role of embodiment in enhancing children's creativity, I further conducted the study with n=19 participants in the absence of a robot, where they played the game only with a tablet. I call this the tablet-only condition (T_C-), where the tablet exhibited non-creative behaviors.

I observed that participants who interacted with the creative robot (R_C+) exhibited more creative behaviors than the participants who interacted with the non-creative robot (R_C-). I saw no significant difference between the non-creative robot (R_C-) and non-creative tablet conditions (T_C-). Three measures of creativity were recorded, (1) the number of ideas that participants generated per droodle, (2) the number of unique themes they explored in their ideas, and (3) the creativity score of each idea. Creativity scores were ranked by blind coders following the Droodle Creativity Task coding system [24]. I observed that participants interacting with the creative robot scored significantly higher in creativity scores in all three measures as compared to participants who interacted with the non-creative robot. I conclude that children can model creativity from a social robot and inform Child-Robot Interaction Patterns that help foster creativity in children. Further, I conclude that mere embodiment without *creativity demonstration* behaviors have no significant effect on children's exhibited creativity.

4.1.2. Study Design

4.1.2.1. Pre test

Standardized Test for Creativity

Participants were administered the first part of the verbal and figural module of the Torrance Test of Creative Thinking. The purpose of conducting the TTCT was to drive a Quasi random assignment into groups such that their creativity scores are balanced across the groups.

4.1.2.2. Participants

51 participants in the 6-10-year-old age group were recruited for the study (24 female, 27 male). All 51 students completed the Torrance Test of Creative Thinking (TTCT) as a part of the pretest activity. 2 participants were excluded from the analysis because of unclear audio transcription or incomplete audio files. 1 participant was excluded from the analysis because they were a non-native English speaker and participated in Spanish. Hence, I conducted the analysis on 48 participants' data (22 female, 26 male). The average age of the participants was 8.06 (S.D. = 1.78).

The subjects were recruited as part of the after-school activities program at the public schools in Somerville, MA. 1 of the subjects had previously interacted with the robot used in the experiment. All students had basic knowledge of robotics and Artificial Intelligence taught to them as a part of another module of the after-school program. All participants and their guardians signed a consent to participate and for audio and video data collection.

I divided the participants in 2 balanced groups such that the mean and standard deviation of the two groups' TTCT creativity scores are balanced [Table 7]. The two groups were also counter-balanced in terms of the participants' age and gender. One group interacted with the creative robot (R_C+ condition) and the other group interacted with the non-creative robot (R_C- condition).

Study groups	**n**	**TTCT scores**	**Gender**	**Age**
Creative robot (R_C+)	24	42.16 ± 7.17	F = 9, M = 15	7.78 ± 1.92
Non-creative robot (R_C-)	24	40.66 ± 6.01	F = 13, M = 11	8.38 ± 1.85

Table 7. 48 participants' gameplay data was analyzed. Participants were divided in balanced groups based on TTCT scores, gender and age.

4.1.2.3. Pilot Study

In order to better design the child-robot interaction, I first conducted a pilot study to playtest the Droodle Game. Instead of a tablet app to display the Droodles, I made use of physical cards displayed in a fixed order that the system is aware of. The purpose of the pilot study was to gain an understanding of, 1. If the game is fun, and what are some ways to make it more playable, and 2. The number of rounds of the game can children play while it does not feel tiring and repetitive. I observed that the game was fun and playable for the children. It was very simple to understand, but I observed that children (especially younger children) caught on faster when presented with an example by the experimenter. Hence, in the main interaction, I made the design decision to include an example. Further, I also observed that 4-5 rounds is a good number of rounds before the participants start feeling tired, and about 30 seconds is a good round duration during which participants keep producing ideas. I conducted the pilot with 9 children.

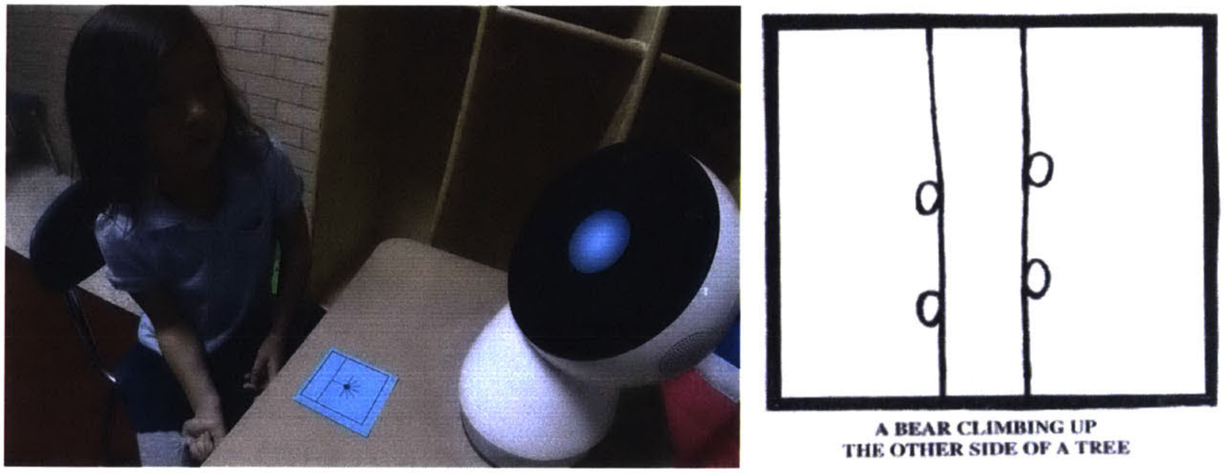


Figure 32.a. Participant playing Droodle Task game with Jibo robot. 32.b. Example of a Droodle image with title.

I collected participants' speech data during the pilot study and analyzed it for creativity scores, and transcribed them. In order to train the blind coders on the Droodle assessment guide developed by Kahn et al. [24], I provided them with this data. I saw early patterns of creativity scores of the participants interacting with the creative being higher than participants that interacted with the non-creative robot [Figure 33]. However, there were too few data points recorded to conclude anything meaningful about the data. Through the pilot study, I could also design the data collection infrastructure of coding each title that participants generated and recording them and storing them internally with the participant's ID. The pilot study helped me design the game interactions on the tablet, train the coders on qualitative data analysis of speech data, put the data collection model in place and set up for the main study.

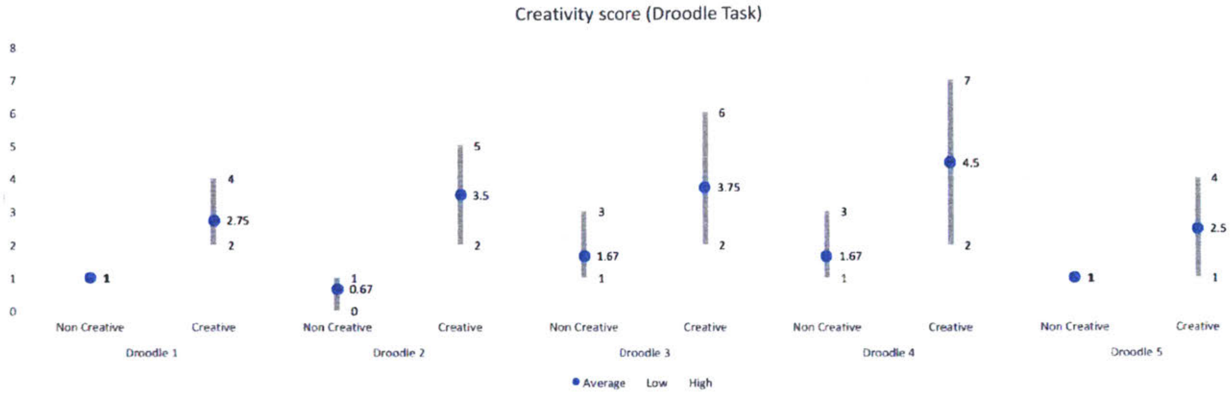


Figure 33 : Preliminary results from Creativity Droodle game. X-axis : Droodle number, and study condition. Y-axis : mean number of title ideas generated by all participants.

4.1.2.4. Main Study

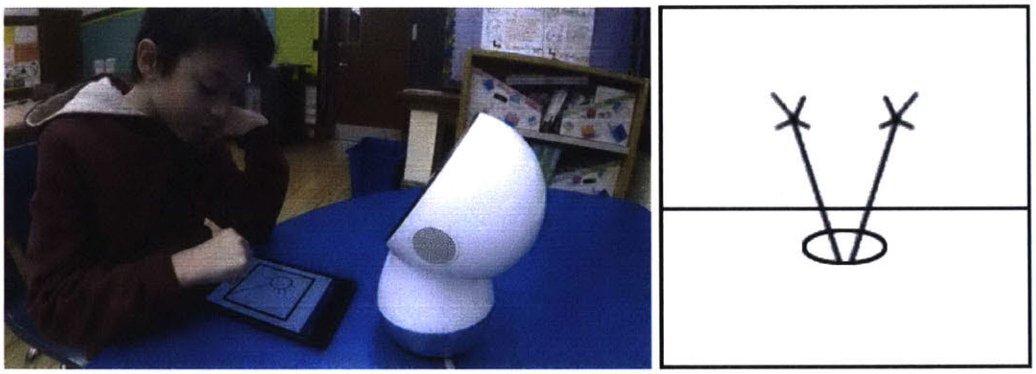


Figure 34.a. Interaction Scene. A child is playing the Droodle Creativity Game on an Android Tablet with the social robot Jibo. 34.b. Example of a Droodle Image. 10 Droodles were used in the Droodle Creativity Game (5 per player).

Study Conditions

All participants were divided into two study-condition groups, one that interacted with the creative robot and one that interacted with the non-creative robot. The groups were divided such that the participants in the two groups were balanced in terms of their mean and standard deviations of TTCT scores, age and gender [Table 7]. The robot exhibits high or low creativity through gameplay and through verbal and nonverbal behaviors. I use Guillford's [4] framework of defining creativity as the ability to generate ideas with fluency, originality and value, to design creative behaviors in gameplay, and Kahn et al.'s Droodle Task Coding system [24] to determine the creativity of Droodle titles.

Creative Robot (R_C+)

Gameplay:

- *Fluency.* The robot generated 4 - 5 ideas per Droodle.
- *Novelty.* The robot explores 3 or more different themes in the ideas generated (by both players).
- *Value.* The robot picks ideas from the library of titles that are tagged medium or high in droodle creativity.

Non-Creative Robot (R_C-)

Gameplay:

- The robot generated 1-2 ideas per Droodle.
- The robot explores 1-3 different themes in the ideas generated (by both players).
- The robot picks ideas from the library of titles that are tagged low or medium in droodle creativity. Low/medium-Droodle title phrases often include very literal descriptions of a picture.

Hypotheses

I hypothesize that the social robot's gameplay behavior can be modelled by children, and that children can learn creative thinking from a social robot. I break down my hypothesis in three parts:

- **H1:** Participants interacting with the creative robot (R_C+) generate a larger *number* of ideas than participants interacting with the non-creative robot (R_C-)
- **H2:** Participants interacting with the creative robot (R_C+) explore more *themes* of ideas than participants interacting with the non-creative robot (R_C-)
- **H3:** Participants interacting with the creative robot (R_C+) generate more *creative* ideas than participants interacting with the non-creative condition (R_C-).

4.1.3. Data Collection and Measures

4.1.3.1. Data Collection

I used the following sensor setup or logging method to collect gameplay data:

- Tablet action logs:
  - Number of titles that children generated for each of the rounds
- Overhead GoPro camera:
  - Video of the interaction (birds-eye view)
  - Audio of the interaction

I made use of Google Cloud's Speech API [17] on the recorded videos, as well as manual transcribing by three researchers blind to the study to transcribe children's phrases.

4.1.3.2. Creativity Measures

Participants' creativity was measured using the Droodle Creativity Game in three parts:

- *Fluency.* The number of ideas that the participants generated.
- *Novelty.* The number of unique themes explored through the ideas. Each idea is associated with theme tags, which include all concepts and keywords included in the idea.

- *Value*. The droodle creativity scores of the ideas generated. The standard metric for analyzing creativity of Droodle titles as suggested by Kahn et al [24] is used. Droodles are graded on the scale of 0, 1, 2, or 3, mapping to non-droodle, low-droodle, medium-droodle, and high-droodle respectively.

For instance, one participant came up with the following ideas for the droodle image in round 1 [Figure 34.b.]: '*It's peppa pig*'; '*It's peppa pig's hands*'; and '*It's frog hands.*' This can be analyzed as: **Number of ideas** =3; **Unique themes** = *"peppa pig", "hands", "frogs";* **Droodle scores**: 2, 3, 2.

4.1.3.3. Condition Analysis

I calculated children's creativity measures (*Fluency* scores, *Novelty* scores, and *Value* of each Droodle title). I further calculated the mean and standard deviation of the *Novelty* and *Value* scores for every Droodle image for each participant. For instance, if for Droodle 1, the participant generated 3 ideas, I calculated the *Novelty* and *Value* as the mean score of the three individual *Novelty* and *Value* scores. I then conducted unpaired T-tests between the creative and non-creative study participants, in order to identify the differences between the two groups, for each of the three creativity scores.

4.1.4. Results

I compared the two study groups' gameplay data to test my hypotheses.

H1: Number of Droodle Ideas

In order to test hypothesis H1, I first analyzed the number of ideas generated by the participants in the two study conditions. I observed that participants who interacted with the robot expressing high levels of creativity (R_C+) generated significantly more overall ideas ($p < 0.01^{**}$) as compared to the participants who interacted with the robot expressing low levels of creativity (C-) [Table 8, Figure 35]. The overall scores were calculated as a mean of their scores across all the study conditions. While participants in the R_C+ group generated a greater number of ideas for all 5 Droodles, the significance of this difference was maintained across 4 out of 5 Droodles (D1: $p < 0.05^{*}$; D2: $p < 0.01^{**}$; D3: $p < 0.05^{*}$; D4: $p < 0.01^{**}$; D5: $p > 0.05$) [Figure 36]. Hence, I confirm hypothesis H1 that participants interacting with the creative robot (R_C+) generated more ideas that children interacting with the non-creative robot (C-).

SG	**D1**	**D2**	**D3**	**D4**	**D5**	**Overall**
R_C+	2.875 ±1.03	3.167 ±1.52	4.25 ±1.62	3.667 ±1.78	2.667 ±1.55	3.325 ±1.16
R_C-	2.125 ±1.15	2.083 ±1.1	3.417 ±1.47	2.417 ±1.13	2.042 ±1.33	2.417 ±0.96
p	<0.05*	<0.01**	<0.05*	<0.01**	>0.05	0.01**

Table 8. Average number of ideas expressed by the R_C+ and R_C- group for each droodle. Participants in the R_C+ condition expressed significantly more ideas than participants in the C- condition. Within each droodle, this difference was significant for Droodles D1, D2, D3, D4.

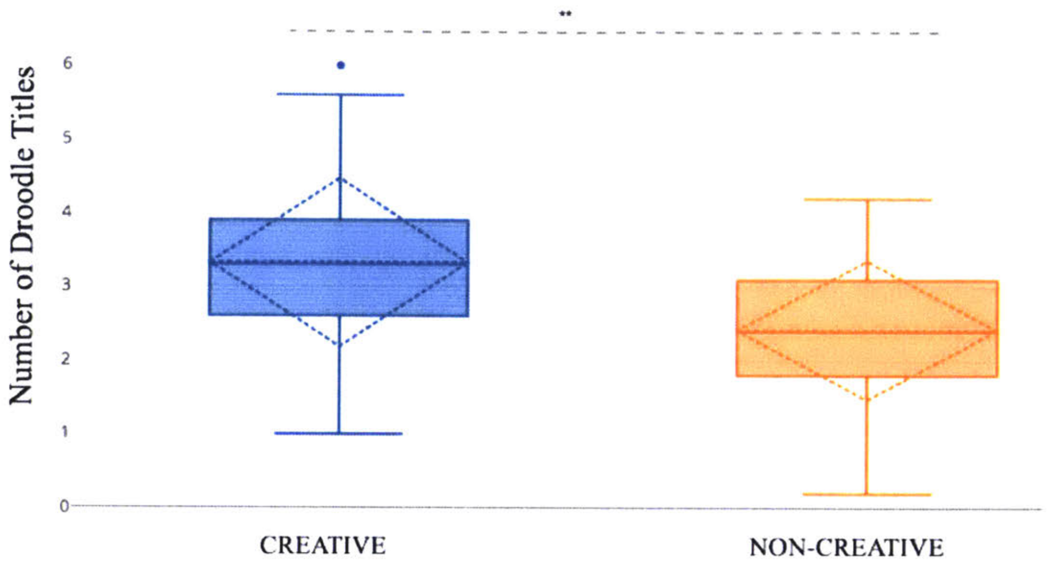


Figure 35. Participants in theR_C+ condition generated significantly higher number of Droodle title ideas as compared to participants in theR_ C- group (p<0.01**)

*Reference for box-plots in the Appendix

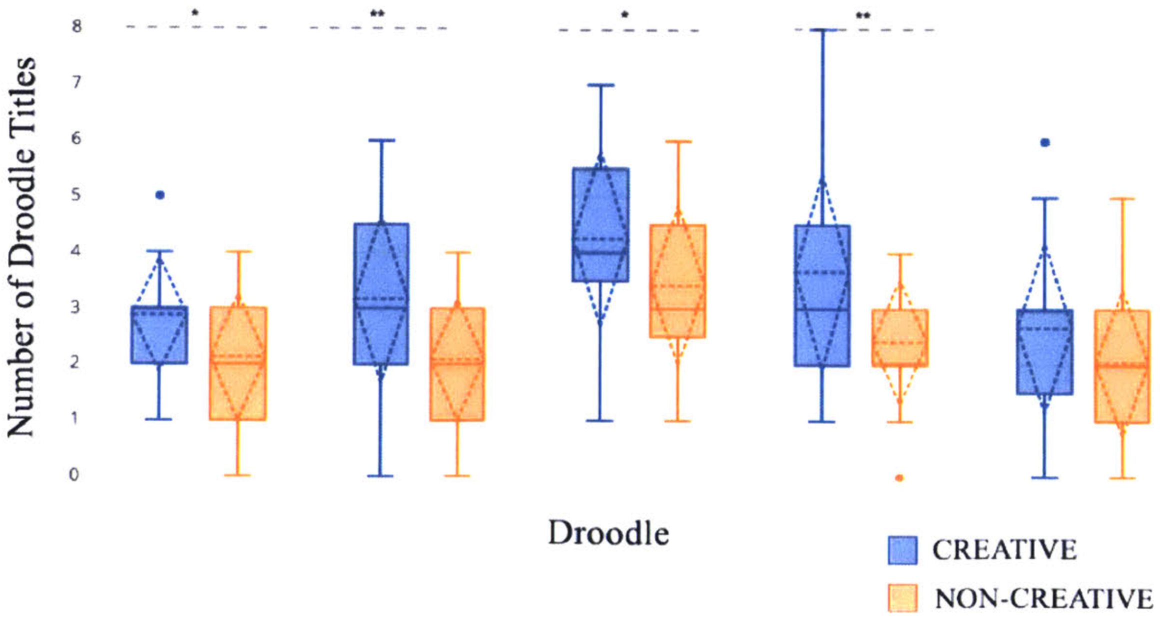


Figure 36. Participants in the R_C+ group generated a greater number of title ideas per Droodle as compared to the C- group for each droodle. This difference was statistically significant for Droodles D1, D2, D3, D4.

H2: Unique Themes Explored in Ideas

In order to understand the novelty and range of Droodle title ideas that participants generated, I looked at the number of unique themes or concepts that constitute each idea. I used Rapid Automatic Keyword Extraction algorithm (Rake NLTK), a Natural Language Processing library to analyze the themes explored in each title [34]. RAKE is a domain independent keyword extraction algorithm which tries to determine key phrases in a body of text by analyzing the frequency of word appearance and its co-occurrence with other words in the text. I observed that participants who interacted with the robot expressing high levels of creativity explored significantly more overall unique themes ($p < 0.01^{**}$) as compared to the participants who interacted with the robot expressing low levels of creativity [Table 8, Figure 37] Participants in the R_C+ explored more themes in all five Droodle tasks, however this difference was significant for 3 out of 5 Droodles (D1: $p > 0.05$; D2: $p < 0.05^{*}$; D3: $p < 0.05^{*}$; D4: $p < 0.01^{**}$; D5: $p > 0.05$) [Figure 38]. Hence, I confirm hypothesis H2 that participants interacting with the creative robot (R_C+) explored more themes of ideas than children interacting with the non-creative robot (C-).

SG	**D1**	**D2**	**D3**	**D4**	**D5**	**Overall**
R_C+	3.917 ±1.55	5.333 ±2.66	5.25 ±1.98	5.75 ±1.7	4.667 ±2.33	4.983 ±1.25
R_C-	3.25 ±2.19	3.75 ±2.32	4.292 ±1.98	4.333 ±2.12	3.583 ±2.44	3.842 ±1.66
p	>0.05	<0.05*	<0.05*	<0.01**	>0.05	<0.01**

Table 8. Average number of unique themes explored by the R_C+ and R_C- group for each droodle. Participants in the R_C+ condition explored significantly more overall unique themes than participants in the R_C- condition. Within each droodle, this difference was significant for Droodles D2, D3, D4.

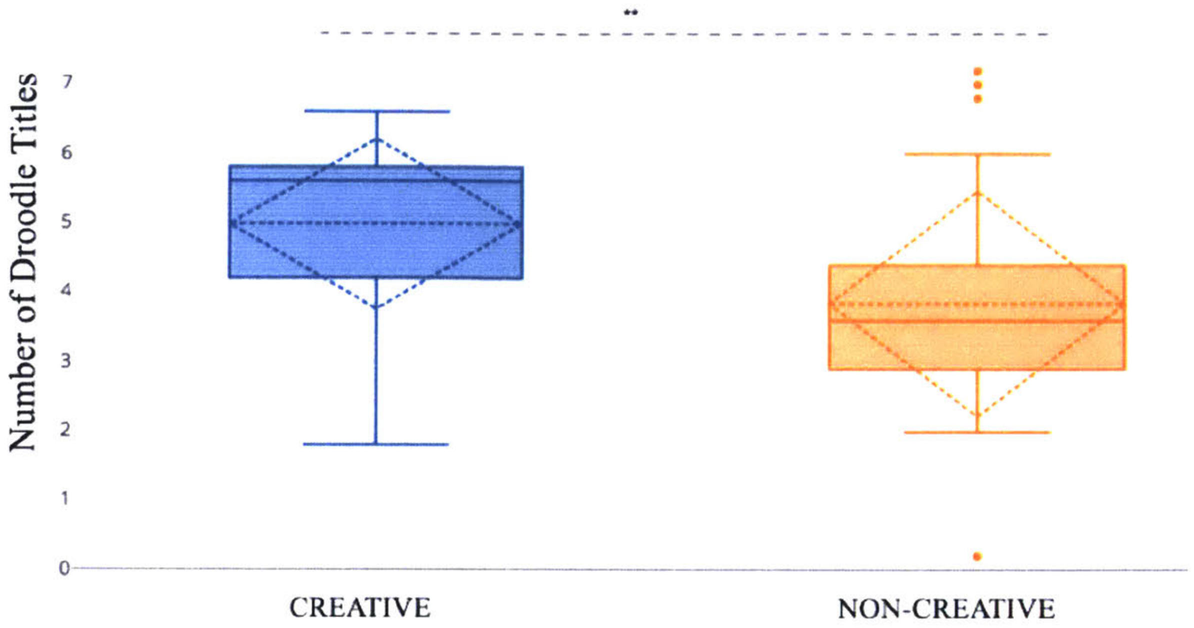


Figure 37. Participants in then R_C+ condition explored significantly higher number of unique themes as compared to participants in the R_C- group (p<0.01**)

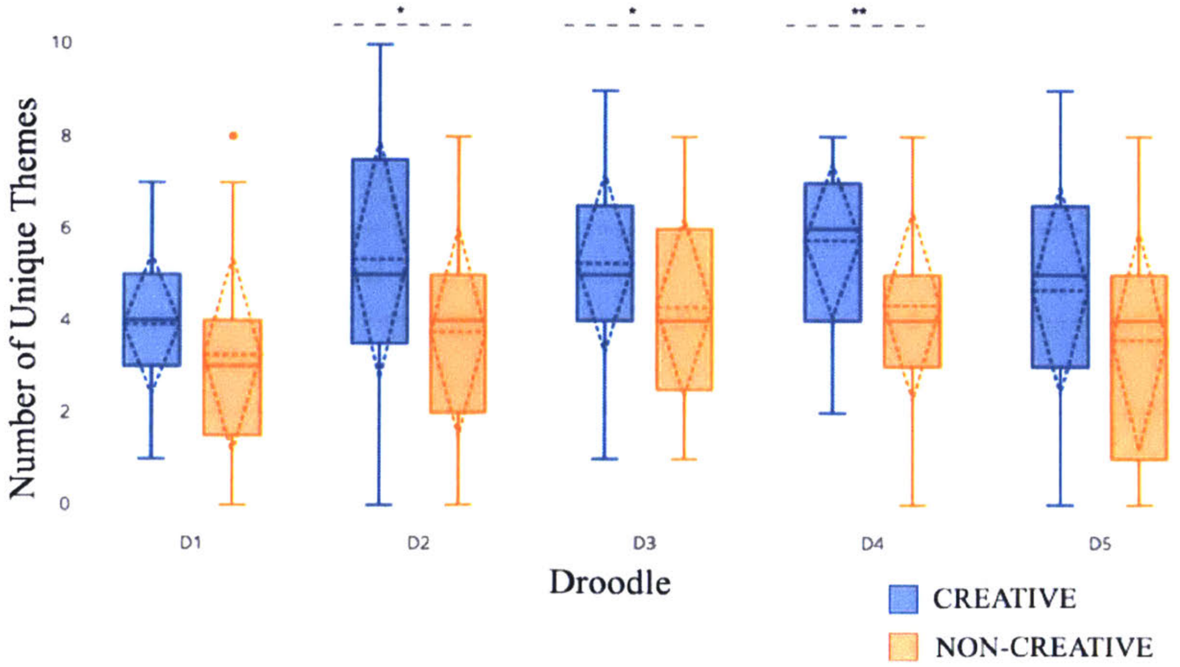


Figure 38. Participants in the R_C+ condition explored more unique themes than participants in the R_C- condition within each Droodle. The difference was significant for Droodles D2, D3, D4.

H3: Creativity Scores

All Droodle titles generated by the participants were coded as 'non-', 'low-', 'medium-' and 'high-droodle' by 3 blind coders. The coders were trained using the Droodle Creativity Task coding scheme. To determine inter-rater reliability between researchers, Cohen's kappa [7] was calculated using 67% of the coded transcripts coded independently by a team member after an initial coding by other two coders. Cohen's kappa was 0.82 which is within the range for substantial agreement considered acceptable for inter-rater reliability.

SG	**D1**	**D2**	**D3**	**D4**	**D5**	**Overall**
R_C+	1.708 ±0.41	1.696 ±0.41	1.401 ±0.41	1.841 ±0.55	2.003 ±0.39	1.73 ± 0.21
R_C-	1.496 ±0.43	1.473 ±0.46	1.134 ±0.43	1.793 ±0.59	1.880 ±0.48	1.532 ±0.25
p	<0.05*	<0.05*	<0.05*	>0.05	>0.05	<0.01**

Table 10. Average creativity scores per Droodle. Participants in the R_C+ condition scored a significantly higher overall creativity score compared to the C- condition. While participants in the R_C+ condition scored higher than participants in the C- condition across all Droodles, the difference was significant for Droodles D1, D2, D3.

An analysis of overall creativity scores for every idea revealed that participants in the creative condition scored significantly higher in creativity score per title than participants in the non-creative condition ($p < 0.01$**) [Table 9, Figure 39]. While the participants in the creative condition scored higher than participants in the non-creative condition for every droodle, the difference was statistically significant in 3 out of 5 Droodles (D1: $p < 0.05$*; D2: $p < 0.05$*; D3: $p < 0.05$*; D4: $p > 0.05$; D5: $p > 0.05$) [Figure 40]. Hence, I confirm H3 that participants interacting with the creative robot (R_C+) generated more creative ideas than children interacting with the non-creative condition (R_C-).

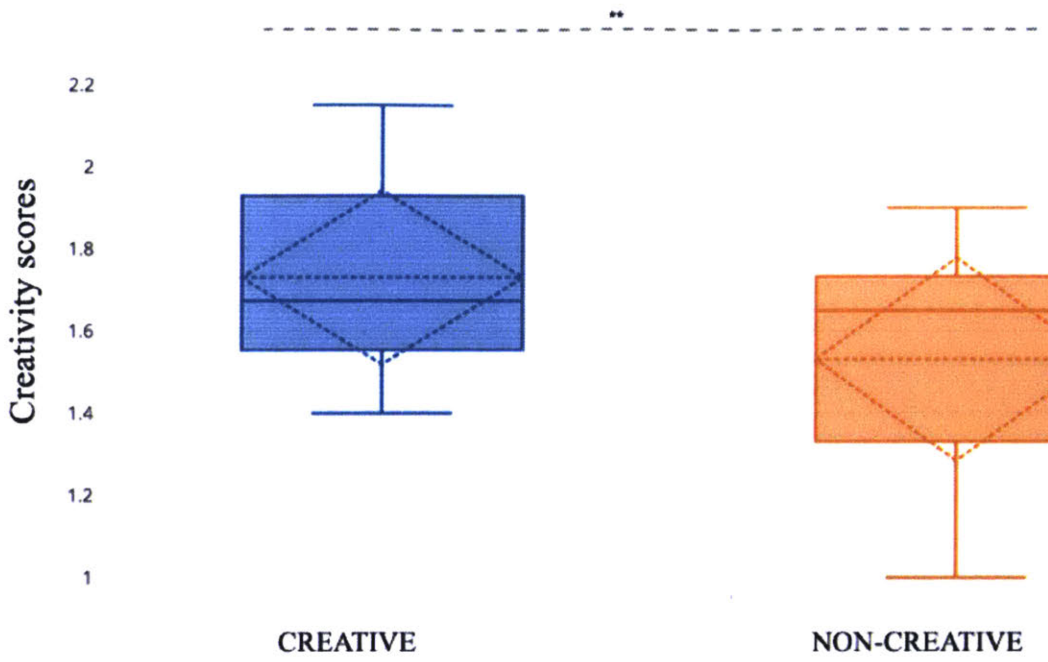


Figure 39. Participants in the R_C+ condition scored a significantly higher overall creativity score as compared to participants in the R_C- condition.

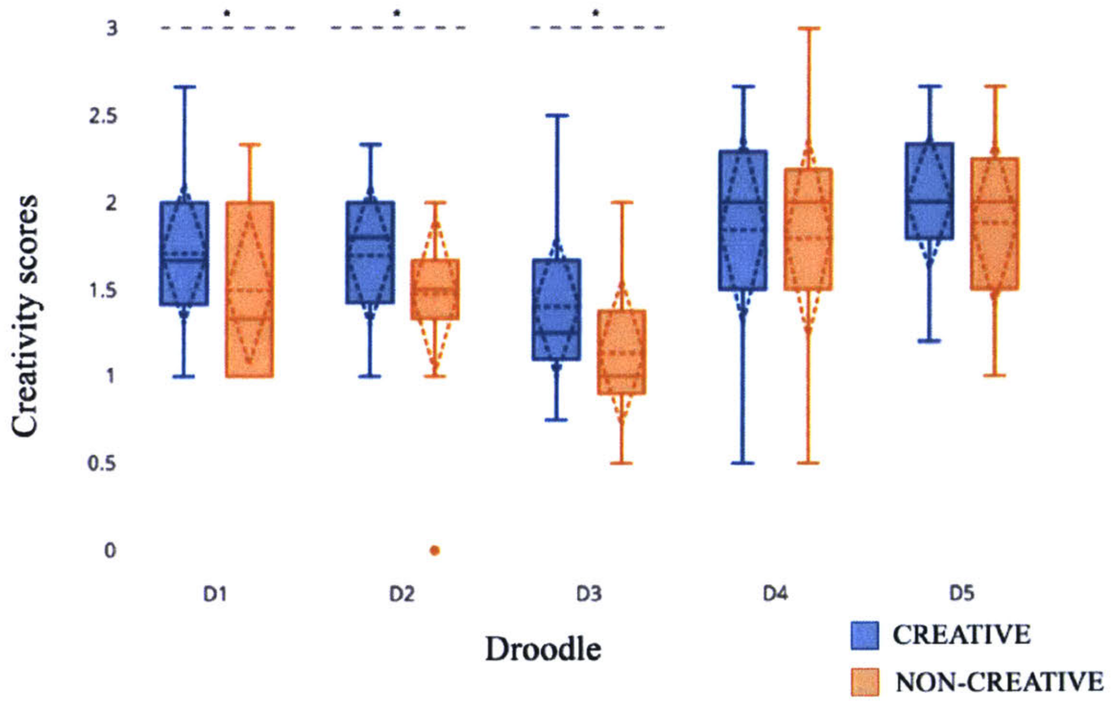


Figure 40. Participants in the R_C+ condition scored higher creativity scores than participants in the C- condition within each Droodle. The difference was significant for Droodles D1, D2, D3.

Through this study, I could confirm all three hypotheses that children model a social robot's verbal creativity constituting of fluency, novelty and value. Children interacting with the social robot that exhibited high creativity scored significantly higher on all of the measures. Droodle wise comparison revealed that the result was not being replicated in the later rounds (D4, D5). One reason for this was that many participants got tired or uninterested near the end and started responding less, leading to less data in Droodle 5. The Droodle images picked in each round were randomized, hence this effect was not a result of the Droodle itself, but of the time of gameplay.

In an attempt to understand how the embodiment of the social robot influences children's engagement, I also ran another user study with 19 participants, where the participants played the same game with only the tablet that played the same gameplay as the non-creative robot. I observed no significant difference in creativity scores between the non-creative tablet condition (T_C-) and the non-creative social robot condition (R_C-), which indicated that just the presence of the robot (without the *creativity demonstration*) does not influence the child's creativity. However, I did observe a change in the times of engagement between the tablet and the robot conditions. Participants stopped playing the game, stating they were tired or bored, or not stating a reason, sooner in the tablet-only condition. In this case, they typically did not respond with any Droodle title. While this was not a part of my original hypothesis, I gained useful insights about how the presence of the robot alone led to greater engagement in the creativity task. There was no significant difference in the times of engagement between the two robot conditions (R_C+ and R_C-).

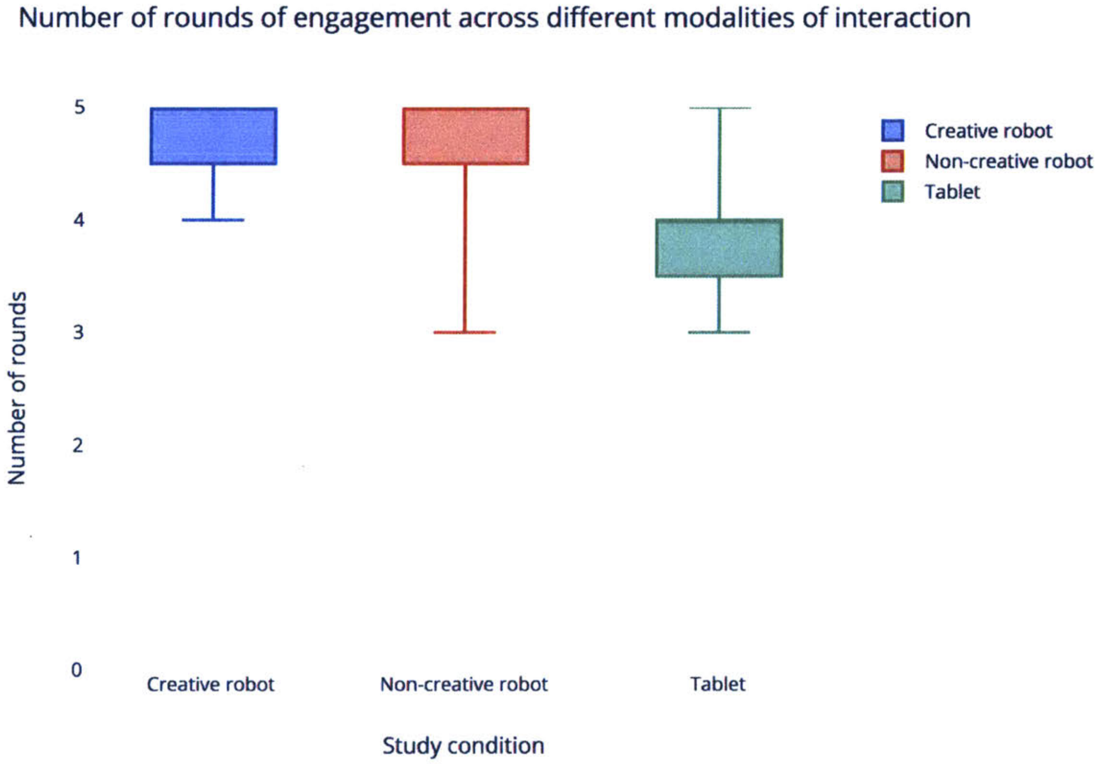


Figure 41. Participants interacted with the robots significantly longer than the tablet. Hence, just the presence of the embodied robot as a game played can increase the engagement, but might not lead to an increase in creativity.

4.2. Figural Creativity with Magic Draw Game

4.2.1. Overview

To investigate whether children model a social robot's figural creativity, I employed the Magic Draw game, which involves a collaborative drawing interaction on an Android tablet between the child and the robot. The gameplay involves one player starting a drawing with one stroke and the other player completing it, before switching turns. I made use of the Sketch-RNN model which generates drawing strokes to convert a starting stroke into a meaningful object. The model was trained on 55 common object categories from the QuickDraw dataset, which is a collection of human drawings. I have described the technical implementation of this autonomous drawing model in **Chapter 3.3.1** above.

To analyze the role of *creativity demonstration* by the robot and the role of *embodiment* on children's creativity, I carried out two randomized controlled trials with 116 children in the 6-10 year old age group. Participants were divided into three groups that were counterbalanced by their creativity scores (as measured by the TTCT test), age and gender [Table 11]. The first group of children interacted with the robot exhibiting creative behaviors (R_C+), the second group of participants interacted with the robot exhibiting non-creative behaviors (R_C-) and the third group of participants interacted with the tablet exhibiting non-creative behaviors (T_C-). Creativity in the study conditions was adjusted both by the creativity of the drawings as well as by robot behaviors. Creativity of drawings in the non-creative robot condition (R_C-) and non-creative tablet condition (T_C-) was reduced by reducing the quality of drawings by adjusting the temperature variable (τ =0.8), reducing the accuracy of picking the right drawing model and reducing the speed of drawing. Creativity of drawings in the creative robot condition (R_C+) was enhanced by reducing the randomness (τ =0.2), increasing the accuracy of picking the right drawing model and increasing the speed of drawing. I have described the technical implementation of the creativity adjustment in the **Study Conditions section (4.2.2.3)** and the validation of this adjustment in the **Results section (4.2.4)** below.

Creativity of all of the participants' and robot's drawings were scored by using the TCT-DP measure of figural creativity **(section 4.3.3)** by coders blind to the study hypothesis and conditions. I first hypothesized that the creative drawing model did indeed draw more creative drawings as compared to the non-creative drawing model. Coders scored the drawings created by the creative drawing model as significantly more creative as compared to those in the non-creative drawing model. Hence, I could verify that the adjustment of models to create drawings of different degrees of creative was effective.

In order to understand the role of *creativity demonstration* exhibited by the robot on children's figural creativity, I compared the creativity exhibited by participants that interacted with the non-creative robot (R_C-) and the creative robot (R_C+). I observed that children who interacted with the creative robot scored significantly higher on creativity measures than children who interacted with the non-creative robot. I conclude that children can model a creative robot's figural creativity.

In order to understand the role of *embodiment* on children's figural creativity, I compared the creativity exhibited by participants that interacted with the non-creative robot (R_C-) and the non-creative tablet (T_C-). This was similar to the study conducted by Alves-Oliveira et al. [51] where they compared children's drawings' creativity measures in the presence and absence of a robot, and found no significant difference in creativity levels. The difference in this study is that we made use of a fully autonomous child-robot interaction and drawing model whereas the drawings were drawn by a human drawer in a *Wizard of Oz* manner in the Alves-Oliveira et al. [51] study. Similar to their WoZ study, I observed that there was no change in children's drawing creativity measures between the robot and the tablet. Hence, it was not just the presence of an embodied robot, but also its behavioral design as a creative artist helped children be more creative.

Children who interacted with the robot were more likely to find the interaction fun as compared to children that interacted with the tablet. Further, children in the R_C+ condition rated the drawings significantly better than the children in the R_C- condition. This was expected since the model was adjusted to draw more or less creative drawings. However, it was surprising that children in the T_C- condition rated the drawings significantly better than the R_C- condition, even though both of them used the exact same drawing model. This may be a result of them having higher artistic expectations from the robot as compared to a tablet.

I conclude that children can emulate a robot's figural creativity, however the mere embodiment of the agent does not seem to have an effect on children's creativity. Children find the game more enjoyable with the robot as compared to with a tablet, and they may have higher artistic expectations from a robot.

4.2.2. Study Design

4.2.2.1. Pre test

Standardized Test for Creativity

Participants were administered the first part of the verbal and figural module of the Torrance Test of Creative Thinking. The purpose of conducting the TTCT was to drive a Quasi random assignment into groups such that their creativity scores are balanced across the groups.

4.2.2.2. Participants

A total of 116 participants in the 6 - 10 year old age group were recruited for the study, including the control tablet-only condition [Table 11]. All participants completed the TTCT as a part of the pretest activity. The subjects were recruited as part of the after-school activities program at the public schools in Somerville, MA. The average age of the participants was 7.5 years (S.D = 1.94).

I divided the participants into three balanced groups such that the mean and standard deviation of the two groups' creativity scores are similar [Table 11]. The three groups were also counterbalanced in terms of the participants' age and gender. One group interacted with the robot offering *creativity scaffolding* (R_C+ condition), one group interacted with the robot that did not offer *creativity scaffolding* (R_C- condition), and a third control group, where the participants played the game on the tablet that did not exhibit *creativity scaffolding* behaviors (T_C-).

Study Groups	**n**	**TTCT scores**	**Gender**	**Age**
Creative robot (R_C+)	37	43.33 ± 6.30	F=14 M=23	7.89 ± 1.91
Non-creative robot (R_C-)	41	42.91 ± 5.16	F=20 M=21	7.09 ± 1.96
Tablet-only (T_C-)	38	41.66 ± 6.01	F=20 M=18	7.61+- 1.92

Table 11. 116 Participants participated in the Magic Draw study. Participants were divided into balanced groups based on their TTCT scores, gender and age.

**It is important to note that 12 of these participants also participated in the other two studies, which can lead to potential biasing of results, but that was not taken into account while analysing the findings. It is also important to note that the study was conducted in four different settings (three schools, and in-lab setting) which can also influence findings.*

4.2.2.3. Study Conditions

Participants were divided into three study conditions :

Creative Robot (R_C+)

The robot exhibited higher creativity by drawing more creative drawings (as defined by the TCT-DP figural creativity test). For the creative robot, creativity was exhibited through the quality of drawings, in terms of drawing creativity metrics described in the TCT-DP test: Continuations (Cn), Completion (Cm), New elements (Ne), Connections made with a line (Cl) between one figural fragment or figure or another, Connections made to produce a theme (Cth) and speed of drawing (Sp) [100]. I adjusted the temperature variable τ (Cm, Cl, Cth) to be 0.2 to reduce the randomness in drawing, and a fully accurate model category match. This led to higher quality drawings with a better model match to the category that the child selects. Further, I kept the speed of drawing to the default speed (60 fps).

In order to exhibit creativity, I also built in some level of creative reflection, where the robot articulates which drawing it is going to make and in some cases, a preset feature match. It would say prompts such as, "*I am now going to make a cat. I will first convert this into ears*". This mapping was not accurate in some cases. Further, the robot also provided positive feedback and expressed higher positive affect after the completion of each drawing as compared to the non-creative robot.

Non-Creative Robot (R_C-)

The robot exhibited lower creativity by drawing low creative drawings (as defined by the TCT-DP figural creativity test). I adjusted the temperature parameter of the generative models to be the 0.8 which increases the randomness of the drawing, leading to lower quality drawings with a lower model match to the category that the child selects. Further, I also adjusted the framerate of rendering to 30 frames per second to generate slower drawings. I also made the model periodically select an incorrect category to make the model seem less of an expert artist.

The robot did not have any reflective speech during the drawing interaction. The robot did not provide positive feedback at the end of the rounds and exhibited less positive affect as compared to the creative robot.

Non-Creative Tablet-only (T_C-)

Participants played the same game but without the robot. Participants were told that the computer will automatically generate drawings and then the turn shifts to them. The gameplay was exactly identical, and the drawing model used was identical to the one used in the non-creative condition.

I also validated this difference of creativity between the C+ condition and the C- conditions by having coders review the drawings created by the model (the robot's drawings) and saw a significant difference in the creativity scores of the drawings.

4.2.2.4. Hypothesis

While I changed model variables to create less creative drawings in the C- conditions (R_C- and T_C-) as compared to the C+ condition (R_C+), I analyzed the actual drawings produced to verify if that was indeed the case. I hypothesize the validity of the creativity difference between the two study conditions:

- **H1:** The drawing model produces more creative drawings in the R_C+ condition than in the R_C- and T_C- conditions.

Further, I hypothesize that children will emulate verbal creativity from a social robot:

- **H2:** Children who played the Magic Draw with the creative Jibo (R_C+) will exhibit higher levels of creativity in their own drawings than children that play with the non-creative Jibo (R_C-).

Lastly, I analyze the role of embodiment on children's creativity:

- **H3:** Children who played the Magic Draw with the non-creative Jibo (R_C-) will exhibit higher levels of creativity in their own drawings than children that play with the non-creative Tablet (T_C-).

4.2.2.5. Post test

In order to understand children's perceptions of the robot's creativity and experience during the interactions, I asked post test questions consisting of likert scales, yes/no questions and open ended descriptive questions:

Q1 : Did you have fun playing the game today? (1-5)
Q2 : Do you think the computer/Jibo helped you finish the drawings?
Q3 : Do you think Jibo's talking was helpful for your drawings? (yes/no)
Q4 : Do you think the computer/Jibo is a better artist than you? (yes/no)
Q5 : How good an artist do you think the tablet/Jibo is? (1-5)

4.2.3. Data Collection and Measures

4.2.3.1. Data Collection

I used the following sensor setup or logging method to collect gameplay data:

- Tablet action logs:
    - All drawings drawn by the child in three rounds
    - All drawings drawn by the robot in three rounds
    - The ratings that children provided of all the drawings at the end of the game.
- Overhead GoPro camera:
    - Video of the interaction (birds-eye view)
    - Audio of the interaction

Researchers conducting the study recorded the post test interview responses of the participants.

4.2.3.2. Creativity Measures

I used the TCT-DP test to analyze the creativity of the drawings. The measure makes use of the following metrics for creativity evaluation:

1. Continuations (Cn): Any use, continuation or extension of the [six] given figural fragments.
2. Completion (Cm): Any additions, completions, complements, supplements made to the used, continued or extended figural fragments.
3. New elements (Ne): Any new figure, symbol or element.
4. Connections made with a line (Cl) between one figural fragment or figure or another.
5. Connections made to produce a theme (Cth): Any figure contributing to a compositional theme or "Gestalt".
6. Boundary breaking that is fragment dependent (Bfd): Any use, continuation or extension of the "small open square" located outside the square frame.
7. Boundary breaking that is fragment independent (Bfi).
8. Perspective (Pe): Any breaking away from two-dimensionality.
9. Humour and affectivity (Hu): Any drawing which elicits a humorous response, shows affection, emotion, or strong expressive power.
10. Unconventionality, a (Uc, a): Any manipulation of the material.
11. Unconventionality, b (Uc, b): Any surrealistic, fictional and/or abstract elements or drawings.
12. Unconventionality, c (Uc, c): Any usage of symbols or signs.
13. Unconventionality, d (Uc, d): Unconventional use of given fragments.
14. Speed (Sp): A breakdown of points, beyond a certain score-limit, according to the time spent on the drawing production.

I had three coders, that were blind to the study's hypothesis and the participants' study condition, review the drawings and rate them. I used these scores for calculating the TCT-DP measures of the drawings. Some participants did not make any drawings, and some drawings were not saved due to network errors. I had a total of 97 drawings (R_C+ = 33, R_C- = 34, T_C- = 33) that I ran analysis on.

4.2.3.3. Condition Analysis

Children's creativity was calculated in terms of the TCT-DP measures. I conducted one-way ANOVA tests between the three conditions and followed by post hoc analysis (if applicable) to reveal any between group differences.

4.2.3.4. Post Test Analysis

I compared the post test self report measures using ANOVA tests (followed by post hoc analysis if applicable) to reveal differences in different study conditions.

4.2.4. Results

H1 : Creativity scores of the robot's drawings

In order to test my hypothesis, I compared the TCT-DP scores of the robot drawings generated by the creative model and by the non-creative model. A t-test revealed that the model type had a significant effect ($p<0.05$*) on the generated drawing's creativity scores. It must be noted that this dataset was smaller than the children's drawing dataset since I did not collect all of the drawings generated by the model. This significant difference helps me establish that the creative model was indeed generating drawings that were more creative than the non-creative model. Hence, the manipulation of the model to adjust temperature, pick categories and adjust drawing speed led to a change in the drawing's creativity.

Model Condition	**n**	**TCT-DP scores**
Creative model (C+)	12	28.91 ± 6.69
Non-Creative model (C-)	15	20.33 ±7.86
p		$p<0.05$*

Table 12. One way ANOVA tests revealed that the study condition has a significant effect on participants' figural creativity

H2 : Creativity scores of the child's drawings in R_C+ vs R_C- &
H3 : Creativity scores of the child's drawings in R_C- vs T_C-

In order to test my hypothesis, I compared the TCT-DP scores of all participants in all the three conditions. A one-way ANOVA test revealed that the study condition had a significant effect on children's figural creativity [F(2, 97) = 12.8, p = 0.00011***].

Study Groups	**n**	**TCT-DP scores**
Creative robot (R_C+)	33	42.27 ± 14.30
Non-Creative robot (R_C-)	34	32.88 ± 9.64
Tablet-only (T_C-)	33	27.75 ± 11.11
p		$p<0.001$***

Table 13. One way ANOVA tests revealed that the study condition has a significant effect on participants' figural creativity

Post hoc analysis revealed a significant difference between the Creative robot (R_C+) and Non-creative robot (R_C-) ($p<0.01$**), as well as between the Creative robot (R_C+) and the tablet condition (T_C-) ($p<0.001$***), where participants scored significantly higher in the Creative robot condition. Even though participants scored higher in the Non-creative condition (R_C-) as compared to the Tablet-only condition (T_C-), this difference was not statistically significant ($p>0.05$).

Study Groups	**n**	**TCT-DP scores**
Creative robot (R_C+) vs Non-Creative robot (R_C-)	67	$p<0.01$**
Creative robot (R_C+) vs Tablet-only (T_C-)	66	$p<0.001$***
Non-Creative robot (R_C-) vs Tablet-only (T_C-)	67	$p>0.05$

Table 14. Post hoc analysis revealed that participants in the Creative (R_C+) condition scored significantly higher than the Non-creative robot (R_C-) and Tablet only (T_C-) conditions.

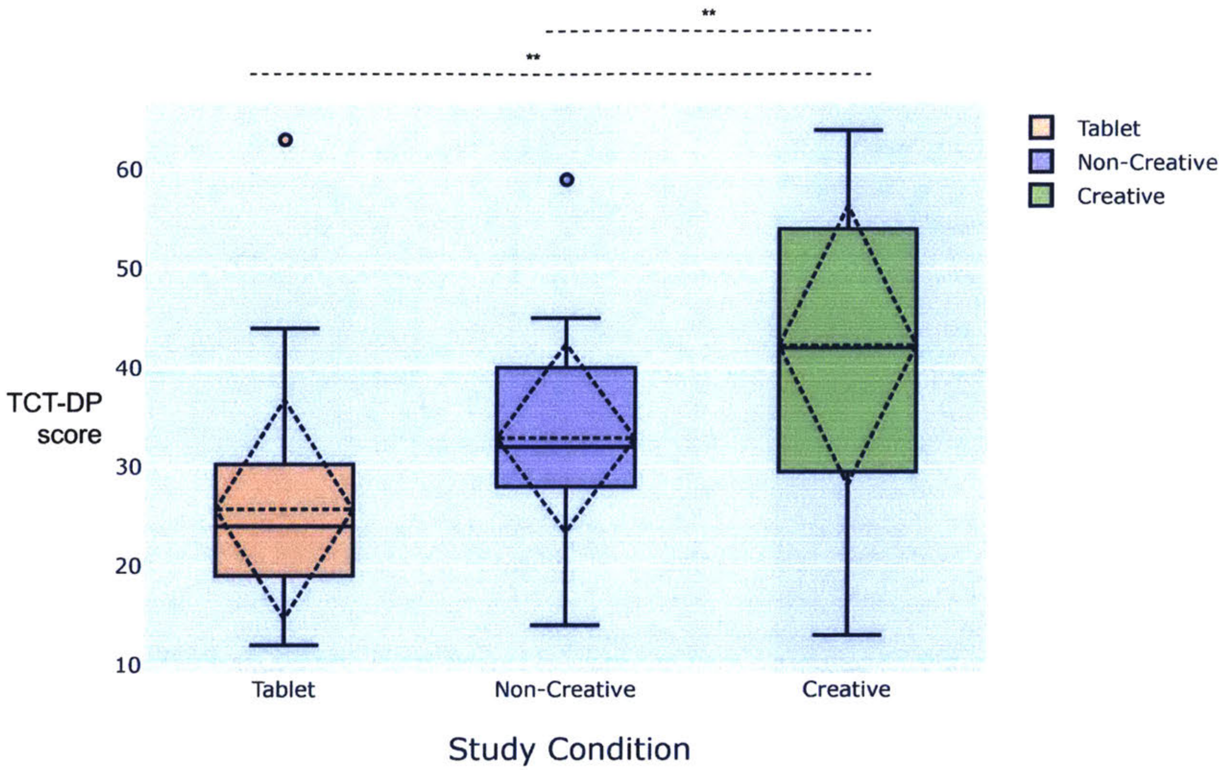


Figure 42. Participants that interacted with the creative robot conditions scored significantly higher on the TCT-DP test compared to the non-creative robot and tablet only conditions.

I found that children that interacted with the creative robot (R_C+) generated drawings that scored significantly higher on creativity, as measured by the TCT-DP. However, when I compared the non-creative robot (R_C-) to the tablet only condition (T_C-), no such significant difference was observed. I could verify hypothesis 2, that children social emulated a social robot's figural creativity, but could not validate hypothesis 3 since the embodiment of the robot alone did not contribute to children's creativity. Hence, in order to foster creativity, it is not merely the presence of the social robot that leads to creative gains, but also the behavior of the robot to itself demonstrate creativity. With this study we demonstrated that children can model verbal creativity from a social robot.

In the post test questionnaire, I learned children's insights about the game interaction, and how they perceive the robot as an artist. I also wanted to learn if they could perceive the robot's creativity and if they thought it assisted them. I asked the following questions in the post test interview:

Q1: Did you have fun playing the game today? (1-5)

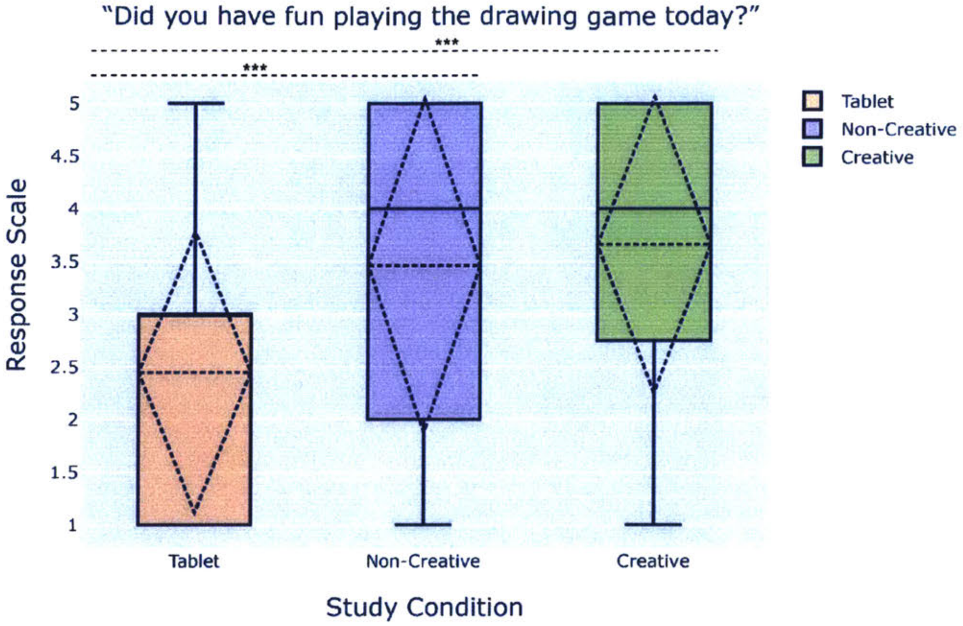


Figure 43. Participants reported to have significantly more fun in the the robot conditions (R_C+ and R_C-) compared to the Tablet-only condition (T_C-).

Analysis revealed that children had significantly more fun with the robot conditions as compared to the tablet only condition (p<0.001***). However, no such significance was found between the two robot conditions. Even though children exhibited higher creativity with the creative robot, they did not report the game to be more fun. However, the presence of the robot made the interaction more fun.

Q2 : Do you think the Computer/Jibo helped you finish the drawings?

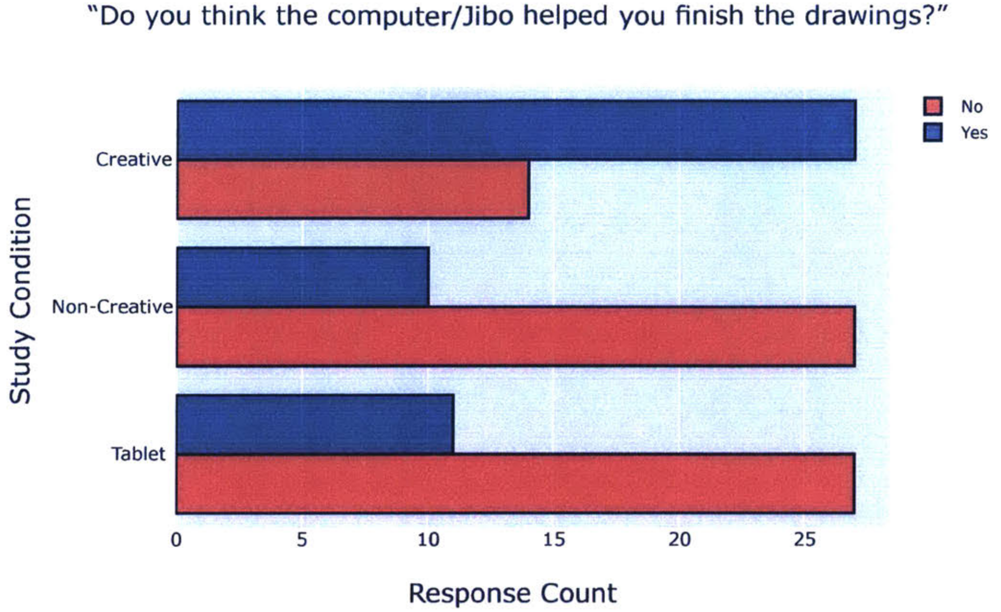


Figure 44. In the Creative robot condition (R_C+) more participants believed that Jibo helped them in finishing their drawings, as compared to the C- and T conditions.

Participants in the creative robot condition reported that Jibo was helpful in finishing their drawings significantly more than participants in the non-creative robot condition. This could be a result of Jibo talking about the drawing process as reflection and making more creative drawings.

Q3 : Do you think Jibo's talking was helpful for your drawings? (yes/no)

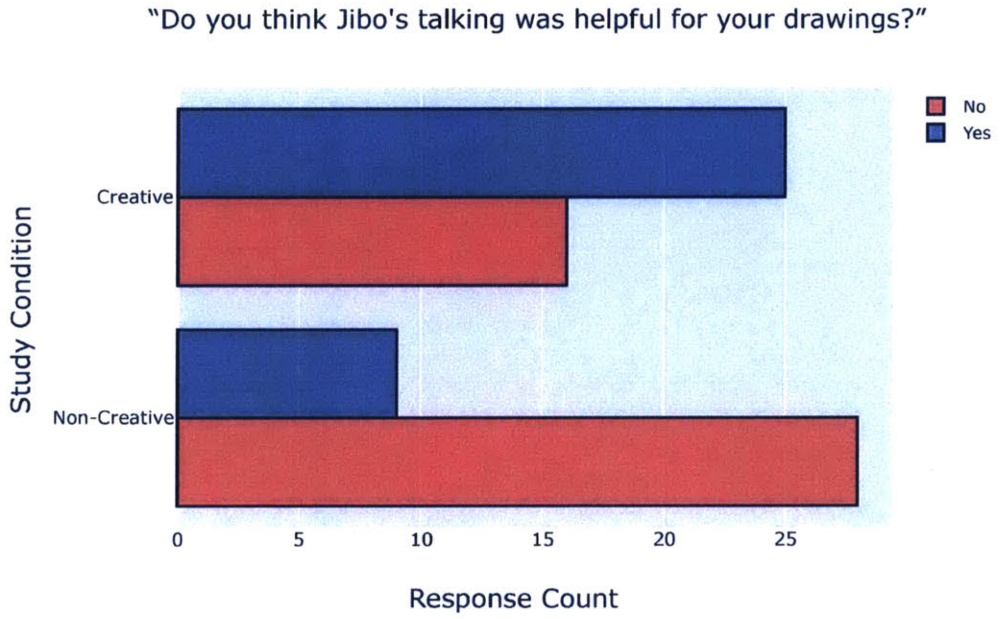


Figure 45. In the Creative robot condition (R_C+) more participants believed that Jibo's talking helped them in finishing their drawings, as compared to the non-creative robot (R_C-) condition

Children in the creative condition thought of the robot's talking to be more helpful, which was an expected result since in the C- condition, the robot did not do any talking during the drawing. One participant said, *"I knew what he was thinking, and that was helping"*. Another one said, *"yes. it was helpful to me when i was asking him what to do and he did it right away, he didn't need other reminders to do it, it is really easy to give him what to do/say."* One child in the creative robot condition said, *"yes, he said good to my drawings."*

Q4 : Do you think Jibo is a better artist than you? (yes/no)

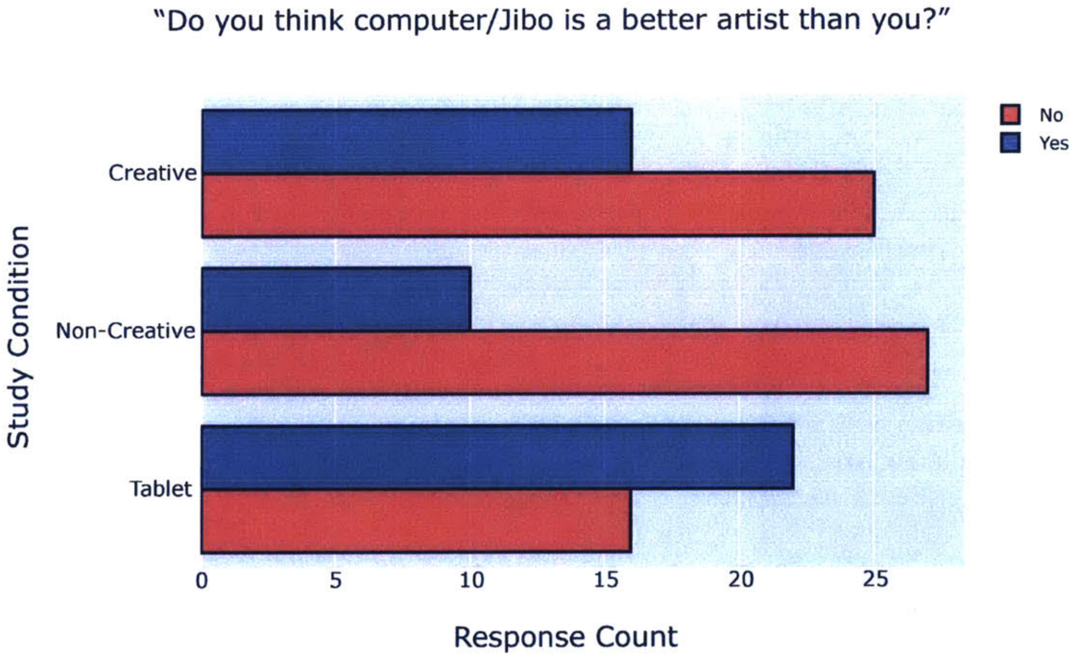


Figure 46. More participants in the R_C+ and R_C- condition believed that they were better artists than Jibo. More children in the Tablet-only (T_C-) condition believed that the computer was a better artist than them.

Even though children in the creative robot condition perceived the robot's creativity, and they demonstrated an increase in creativity scores, they still did not think that the robot was a better artist than them.

Q5 : How good an artist do you think the tablet/Jibo is? (1-5)

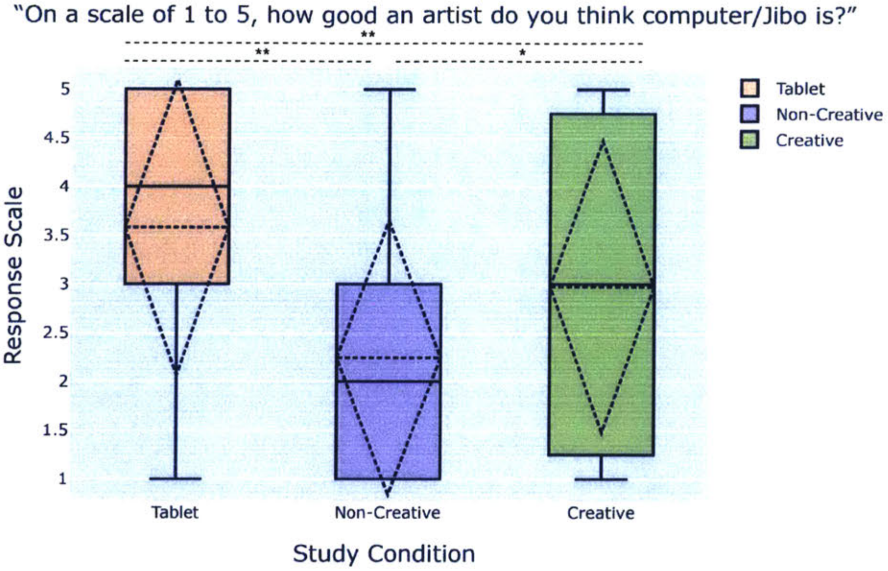


Figure 47. Participants in the tablet only condition reported the tablet's artistic abilities to be significantly higher than both the robot conditions (*p*<0.01**). Participants in the creative robot condition perceived the robot to be more creative than the children in the non-creative robot condition (*p*<0.05*).

Participants were asked how good an artist do you think the tablet or Jibo is. Participants in the tablet only condition reported the tablets artistic abilities significantly higher than both the robot conditions (*p*<0.01**). Further, participants in the creative robot condition perceived the robot to be more creative than did the children in the non-creative robot condition (*p*<0.05*). Even though the tablet-only and non-creative robot used the exact same drawing model, children perceived the tablet to be more artistic than Jibo. This could imply that children have higher expectations of creative abilities from a robot than from a tablet. This could also be a result of Jibo's speech sometimes not matching with his drawing due to delays and imperfect models. One participant in the tablet only condition said, *"It is not a good artist, but it is good for a tablet."*

Further, children in the creative condition could successfully perceive the higher quality of drawings and rated the robot higher on drawing abilities as compared to the non-creative condition. This result was not unexpected since the interaction was designed to have more creative drawings in the creative condition. However, it is important to note that children in all three conditions did not rate the drawing model very well (tablet = 3.57, non-creative robot = 2.24 , creative robot = 2.9). This is a result of the model being trained on a dataset of rough 10 second doodles, which suggests that there is space for improvements in generative drawing models.

Chapter 5 : Investigation II : Can Robots Scaffold Children's Creative Learning

As described in **Chapter 3**, I designed the WeDo Construction Activity which involves the child and the robot Jibo collaboratively constructing models using the WeDo 2.0 Construction Kits. During the interaction, the robot offers *creativity scaffolding* to the child in the form of reflective questions, challenges, ideas and positive reinforcement. Robot behaviors are controlled by a human instructor using a remote control GUI that was co-designed with the instructors.

I hypothesized that the robot's *creativity scaffolding* behaviors can enhance children's *construction creativity*. Further, I hypothesized that the robot's embodiment could have a positive effect on children's creativity. In order to test my hypothesis, I ran a randomized controlled trial with 62 children in the 6 - 10 year old age group. Participants were divided into three groups, counterbalanced by age, gender and creativity scores as measured by the TTCT verbal and figural tests :

- Creative robot group (R_C+) : This group interacted with the robot exhibiting *creativity scaffolding* behaviors.
- Non-creative robot group (R_C-) : This group interacted with the robot that did not exhibit *creativity scaffolding* behaviors.
- Non-creative tablet-only group (T_C-) : This group played the same games in the absence of a robot, only with a tablet, where the tablet did not exhibit *creativity scaffolding* behaviors.

All three groups started with the robot or the tablet providing the same set of basic instructions to help the child make a rover model, after which they are left to explore and make their own models. The creative robot continues to offer scaffolding in terms of asking reflective questions, challenging the participants, and collaboratively ideating with them. The robots were controlled by human instructors in a *Wizard of Oz* manner by a remote control interface. Children's creativity was measured in terms of the number of different ideas they generate, the number of new programming blocks they use and how uncommon their ideas are.

I observed that children that interacted with the *creativity scaffolding* robot (R_C+) scored higher than the non-creative robot and tablet groups (R_C- & T_C-) on all the measures but the results are statistically significant only for the number of ideas and the number of new programming blocks used. I compared the tablet-only condition (T_C-) to the non-creative robot (T_C-) condition and observed no statistical significance on any of the measures. Hence, I could conclude the *creativity scaffolding* behavior designed for the robot is indeed effective in fostering *construction creativity* in young children. Below, I outline the study design and results of the study.

5.1. Study Design

5.1.1. Pre test

Standardized Test for Creativity

Participants were administered the first part of the verbal and figural module of the Torrance Test of Creative Thinking. The purpose of conducting the TTCT was to drive a Quasi random assignment into groups such that their creativity scores are balanced across the groups.

5.1.2. Participants

62 participants in the 6-10-year-old age group were recruited for the study (28 female, 34 male). All 62 students completed the Torrance Test of Creative Thinking (TTCT) as a part of the pretest activity. The average age of the participants was 8.11 (S.D. = 1.68).

The subjects were recruited as part of the after-school activities program at the public schools in Somerville, MA. Several subjects had previously interacted with the robot used in the experiment, and this factor was not controlled for. All students had basic knowledge of robotics and Artificial Intelligence, taught to them as a part of another module of the after-school program. All participants and their guardians signed a consent form to participate and for audio and video data collection.

I divided the participants into three balanced groups such that the mean and standard deviation of the two groups' creativity scores are similar [Table 15]. The three groups were also counterbalanced in terms of the participants' age and gender. One group interacted with the robot offering *creativity scaffolding* (R_C+ condition), one group interacted with the robot that did not offer *creativity scaffolding* (R_C- condition), and one group did the activity with instructions form a tablet, in the absence of a robot (T_C- condition).

Study Groups	**n**	**TTCT scores**	**Gender**	**Age**
Creative (R_C+)	23	42.16 ± 7.17	F=11 M=12	8.3 ± 1.57
Non-Creative (R_C-)	20	40.66 ± 6.01	F=8 M=12	7.65 ± 1.85
Tablet (T_C-)	19	44.16 ± 5.66	F = 9, M = 10	8.2 ± 1.61

Table 15. 62 participants participated in this study. Participants were divided in balanced groups based on TTCT scores, gender and age.

5.1.3. Study Conditions

All participants were divided into three study-condition groups, one that interacted with the robot offering *creativity scaffolding* (R_C+), one that interacted with the robot not offering *creativity scaffolding* (R_C-), and one where participants performed the same tasks in the absence of a robot and with the same instructions provided on a tablet screen, without the *creativity scaffolding* (T_C-). The groups were divided such that the participants in the three groups were counterbalanced in terms of their mean and standard deviations of TTCT scores, age and gender [Table 15]. Both the robots and the tablet start with providing the same set of basic instructions to help the child build and program a rover model that incorporates a sensor and a motor, after which they are left to explore and make their own models. The creativity scaffolding robot (R_C+) continues to offer scaffolding in terms of asking reflective questions, challenging the participants, and collaboratively ideating with them, listed in Table 5. The *non-creativity scaffolding* robot (R_C-) and the tablet (T_C-) prompt the child to explore and make new things, and only participates to answer questions beyond that.

5.1.4. Hypotheses

In order to understand the effect of *creativity scaffolding* on children's creativity, I hypothesized that participants who interacted with the robot offering *creativity scaffolding* exhibit higher levels of creativity in the WeDo construction task. I divide this hypothesis in three parts derived from the three ways of assessing creativity behaviors during the task:

- **H1 :** Participants who interact with the robot offering *creativity scaffolding* (R_C+) come up with a greater number of ideas and use cases for the rover than those who interact with the robot without *creativity scaffolding* (R_C-).
- **H2 :** Participants who interact with the robot offering *creativity scaffolding* (R_C+) use a higher number of new programming blocks (excluding the blocks used in the instructions) than those who interact with the robot without *creativity scaffolding* (R_C-).
- **H3 :** Participants who interact with the robot offering *creativity scaffolding* (R_C+) generate more uncommon ideas than those who interact with the robot without *creativity scaffolding* (R_C-).

In order to understand the role of *embodiment* of children's creativity, I further hypothesized that participants who interacted with the non-creative robot (R_C-) exhibit higher levels of creativity than participants in the non-creative tablet (T_C-) condition. I divide this hypothesis in three parts derived from the three ways of assessing creativity behaviors during the task:

- **H4 :** Participants who interact with the robot without *creativity scaffolding* (R_C-) come up with a greater number of ideas and use cases for the rover than those who interact with the tablet without *creativity scaffolding* (T_C-).
- **H5 :** Participants who interact with the robot without *creativity scaffolding* (R_C-) use a higher number of new programming blocks (excluding the blocks used in the instructions) than those who interact with the tablet without *creativity scaffolding* (T_C-).
- **H6 :** Participants who interact with the robot without *creativity scaffolding* (R_C-) generate more uncommon ideas than those who interact with the tablet without *creativity scaffolding* (T_C-).

5.1.5. Post-test

I conducted an open-ended descriptive post test interview with all participants in order to understand how they perceived their creation and how the scaffolding interaction helped them create. I administered the following questions:

Q1. Can you describe what you made today?
Q2. How do you think the tablet/Jibo was helpful to you?
Q3. How do you think the tablet/Jibo can be of more help?
Q4. Do you think the tablet/Jibo had any creative ideas?

5.1.6. Post-study debriefing

Post conclusion of all the studies, the instructor from the after-school program, debriefed the children about the robot being remote controlled by human instructors in this task. They described how they could observe the participants' actions and they provided dialogues and actions for the robot to perform. Ideally, this debriefing should happen by the experimenter and on an individual level immediately after the task, to ensure that all the participants have an accurate expectation of the robot's abilities.

5.2. Data Collection and Measures

5.2.1. Data Collection

I logged the following gameplay data:

- ROS messages
    - All robot interactions initiated by the instructors using the GUI.
- Tablet action log
    - All actions on the programming application that children used through Android action log.
    - Snapshot of visual programming interface every time the child ran the code on the WeDo controller.
- Overhead GoPro camera:
    - Video of the interaction (birds-eye view)
    - Audio of the interaction

I used Google ASR to record the child's speech, convert it to text and display it on the remote control GUI during the interaction. Researchers conducting the study recorded the post test interview responses of the participants.

5.2.2. Creativity Measures

The creativity exhibited and novelty of ideas that the child comes up with are reported by 2 reviewers who watched videos of the activity. The reviewers were blinded to the study condition that the child was in and blinded to the study hypothesis, but were made aware of the WeDo construction activity. I made use of the creativity correlates of *fluency* of ideas, *novelty* of ideas, unusual uses test and divergent thinking to suggest creativity assessment measures in the construction task. I used the following four behaviors as metrics of creativity:

1. *Number of ideas or use cases for the rover.* The instructions with which the robot guides the child involve sensing values from a motion sensor and using it as input to actuate the rover. This introduces children to logic and conditional statements which are core parts of programming. This core concept can now be applied to many different applications. For instance, children programmed an obstacle course, or used the waving of their hand to display their image, or made a robot follow their hand. I counted the number of unique applications they came up with in the free exploration time as a measure of creativity. This is inspired from the *fluency* and originality of ideas measure, which is a part of several creativity measures [99]. This number is calculated by observing the video stream of the interaction.
2. *Number of new programming blocks used.* The instructions teach children how to use some blocks, such as the condition, motor, sensor, start and stop. However, the WeDo programming interface has many different blocks that can be used in different ways, such as, the image block, the sound block, other motor blocks, the text block, loops, etc. This measure is inspired from *originality* as a measure of creativity. This number is calculated by analyzing the datalog of the tablet interactions.

3. *Commonality*. For each of the new use cases or application ideas of the rover, I looked at how uncommon the idea was. For doing this, I grouped and coded all ideas that were identical or similar, such as, 'obstacle course' and 'lego path'. I then looked at the frequency of that idea in the data. For participants with multiple applications of the rover, I took an average of the two frequencies to report originality. If an idea is uncommon, or deviates from the typical ideas of the group, then, in accord with assessment measures of divergent thinking, they count as more creative [99]. I report the frequencies of each application idea, which is inversely proportional to creativity. This measure is inspired from *divergent thinking* measures, looking at deviations from the group's trends.

5.2.3. Conditional Analysis

I calculated children's creativity measures in terms of the number of ideas for the rover, number of programming blocks used and the commonality of each of the ideas. These were calculated by coding the video recording of the interaction. I conducted a one way ANOVA test between the three study conditions for each of these measures (*creativity scaffolding* robot, *non-creativity scaffolding* robot, tablet-only). Further, I conducted a post hoc analysis to check for groupwise significance.

5.3. Results

I compared the three study group's interaction data to test my hypothesis. I clubbed the hypothesis by the creativity metrics across the three conditions for analysis (H1 & H4; H2 & H5; H3 & H6).

SG	**n**	**Number of ideas for the rover**	**Number of new blocks**	**Frequency of ideas**
Creative robot (R_C+)	19	1.74 ± 1.28	5.96 ± 1.77	0.82 ± 1.03
Non-creative robot (R_C-)	20	1.05 ± 0.76	4.75 ± 1.65	1.21 ± 1.08
Tablet-only (T_C-)	23	0.79 ± 0.71	4.58 ± 2.03	1.25 ± 0.85
p		*p<0.01***	*p<0.05**	*p>0.05*

Table 16. Participants in the Creative robot condition came up with a significantly higher number of ideas, and used significantly higher number of programming blocks than the Non-creative robot (R_C-) and Non-creative tablet-only (T_C-) conditions.

H1: Number of ideas or use cases for the rover in R_C+ vs R_C-

H4: Number of ideas or use cases for the rover in R_C- vs T_C-

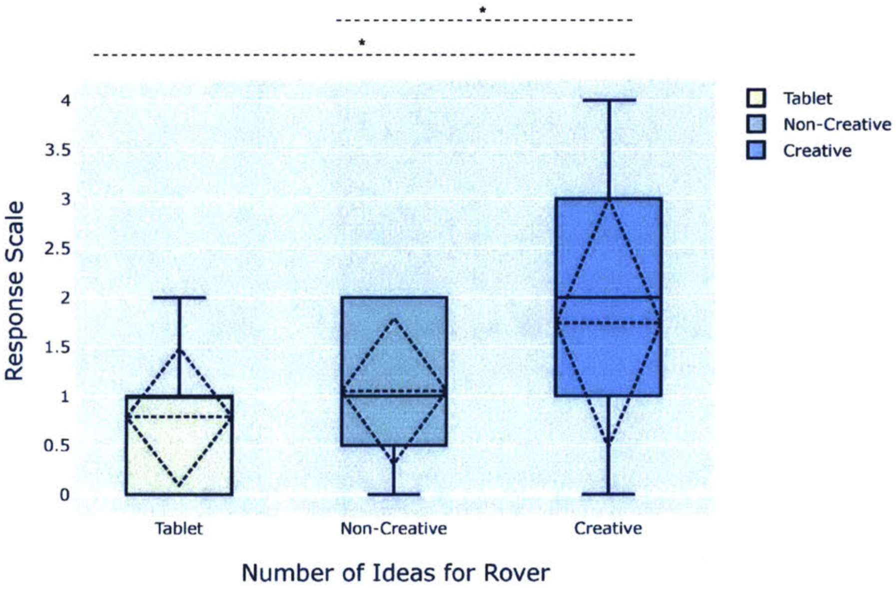


Figure 48. Participants in the Creative robot condition (R_C+) generated a significantly higher number of ideas than in the Non-creative robot(R_C-) and tablet-only (T_C-) conditions.

In order to test hypothesis H1 and H4, I first compared the number of ideas generated by the participants in the three study groups. I conducted a one-way ANOVA test and found that the study condition had a significant effect on children's number of ideas [F(2, 59) = 5.37, p = 0.007]. Post hoc analysis revealed that the creative robot condition (R_C+) was significantly different from both the non-creative robot (R_C-) and tablet-only conditions (T_C-) (p<0.05*). No such significance was found between the non-creative robot (R_C-) and the tablet-only condition (T_C-) . Hence, I confirm hypothesis H1 that the that the participants who interacted with the robot exhibiting *creativity scaffolding* behaviors (R_C+) generated more ideas or use cases for the rover than the participants that interacted with the robot that did not exhibit *creativity scaffolding* behaviors (R_C-). Further, I reject the hypothesis H4 that children that interacted with the non-creative robot (R_C-) exhibited significantly more number of ideas for the rover that participants in the tablet-only conditions (T_C-). Hence, it is the *creativity scaffolding* offered by the robot and not merely the *embodiment* of the robot that influences the number of ideas that children generated.

H2 : Number of new programming blocks used in R_C+ vs R_C-

H5 : Number of new programming blocks used in R_C- vs T_C-

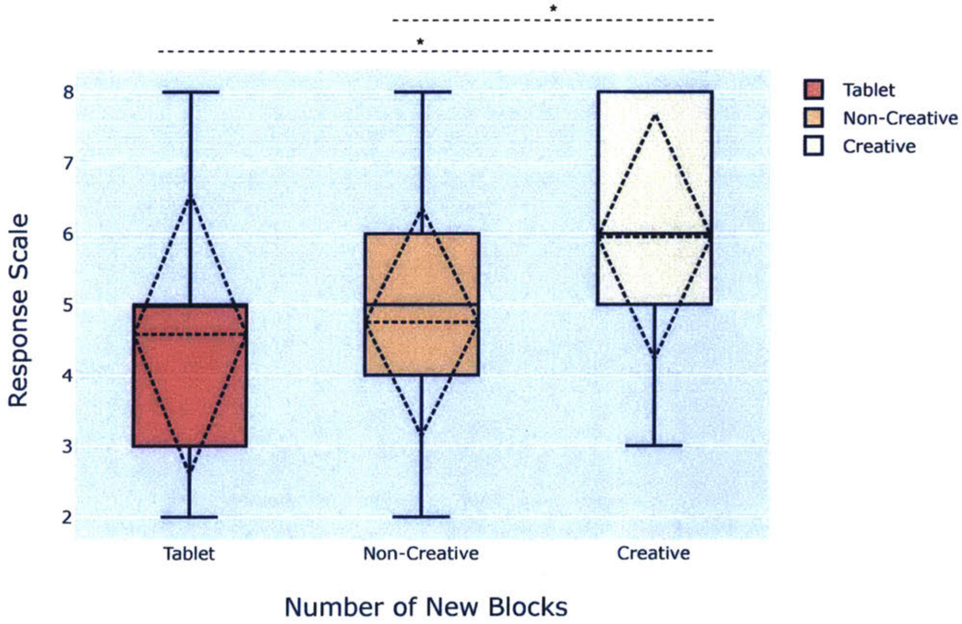


Figure 49. Participants in the Creative robot condition used a significantly higher number of programming blocks than participants in the Non-creative and the Tablet-only conditions.

In order to test hypothesis H2 and H5, I first compared the number of new programming blocks used on the visual programming interface in the three study groups. I conducted a one-way ANOVA and found that the study condition had a significant effect on the number of new programming blocks used by the children [F(2, 59) = 3.68, p = 0.031]. Post hoc analysis revealed that the creative robot condition was significantly different than both the non-creative robot and tablet-only conditions (*p<0.05**). No such significance was found between the non creative robot and the tablet-only condition. Hence, I confirm hypothesis H2 that the participants who interacted with the robot exhibiting *creativity scaffolding* behaviors (R_C+) used a greater number of new programming blocks beyond the ones used in the instructions to construct their models as compared to the participants who interacted with the robot exhibiting that did not exhibit *creativity scaffolding* behaviors (R_C-). This result was in line with the results of H1, since a greater number of rover application ideas will lead to an increase in the number of different programs that children use to code the rover, which would inadvertently lead to an increase in the number of blocks used. I reject hypothesis H5 that participants interacting with the non-creative robot (R_C-) use greater number of blocks as compared to participants interacting with the non-creative tablet (T_C-). Hence, it is the *creativity scaffolding* offered by the robot and not merely the presence of the robot that led to a significant effect on the number of programming blocks used.

H3 : Commonality of ideas in R_C+ vs R_C-

H6 : Commonality of ideas in R_C- vs T_C-

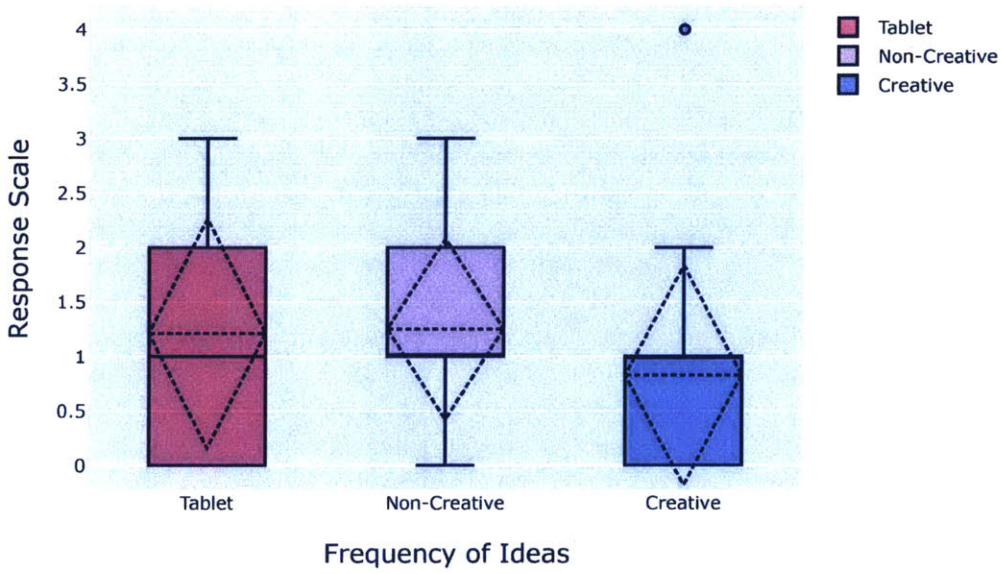


Figure 50. There was no significant difference in the frequency of the ideas that participants generated in the three study conditions.

In order to test hypothesis H3 and H6 that participants that interacted with the creative robot generated uncommon or atypical ideas that were different from the group. I compare the frequency of each idea that the participant had about the rover in the three study conditions. I conducted a one way ANOVA test and found that the study-condition did not have a significant effect on the commonality of their ideas [F(2, 59) = 1.208, p = 0.305]. Post hoc analysis revealed that ideas generated by participants in the creative robot condition were more novel/uncommon than both the non-creative robot and tablet-only conditions , but this difference was not significant ($p>0.05$). Hence, I reject hypothesis H3 that *creativity scaffolding* offered by the robot had a positive effect on the novelty of participants' ideas. Further, I reject hypothesis H6 that embodiment of the robot had a positive effect on the novelty of participants' ideas.

Through conducting the post test interviews, I learned how participants perceived the robot's scaffolding behavior and their comments about how it could be improved. Below, I present a few insights from what the post test interviews revealed:

Q1. Can you describe what you made today?
I first asked participants to reflect on their designs and talk about what they made. Reflection and sharing are key parts of any creative process. Participants responded with a description of what they constructed, what they used, and what they learned. One participant said, "*I made him drive, make music and show an image*". Another participant said, "*I made a LEGO robot that when you put your hands to it it'll go back but without you touching it, and then I made a sensor and I made it make a noise*". One participant said they made "*a spaghetti one-eyed snail cricket thing*". This helped me unpack not only what their ideas were and which bricks they used, but also what their perceptions of their constructions were. Some participants also spoke about ideas they had but could not construct due to time constraints. One participant said, "*I wanted to make the rover move around and find all the walls, but I there was no time.*" I also used participants' narratives of what they made to match with the *number of ideas* metric that was reported by the blind reviewer.

Q2. Was the tablet/Jibo helpful to you? How?
Almost all participants responded with yes, he was helpful. 9 participants provided no reasoning. 5 participants said no (both *non-creativity scaffolding* conditions). The most common reasoning response in both study conditions was that the tablet or Jibo helped them construct the rover by providing instructions. Some participants in the creative condition pointed out how, "*Jibo had cool ideas*" and "*He helped me think of other uses for the sensors*". Multiple participants pointed how how Jibo "*told me when I was doing well, or when he liked my ideas.*" Hence, children did notice the positive reinforcement provided by the scaffolding robot. One participant in the *non-creativity scaffolding* condition said, "*He kind of was [helpful], but he's super rude. Because half the time I tried to say Jibo, can you help me. He will interrupt me with something else. I tried to say good morning but he didn't reply. it takes him a while to respond like he's not listening.*" This highlighted some technical difficulties such as speech delays due to network inconsistencies in implementing this scaffolding model that must be kept in mind. I also learned that rapport building utterances such as longer conversation and greeting utterances in the beginning can help the children establish a common ground with the robot and also help understand that sometimes there are delays in his speech.

Q3. How do you think the tablet/Jibo can be of more help?
Participants had very valuable feedback about making the interaction better. In the tablet-only condition, one participant said, "*It would be helpful to go back to old instructions, or if you could ask questions to the person.*" The most common response I received in both the robot conditions was that it would be nicer if the robot displays the blocks to be used on his screen, and that it is difficult to understand which block he is talking about in speech alone. Unlike a human instructor, a robot cannot point, and hence visuals would be very helpful. One participant said, "*He could have shown me other things that the rover can do*". One participant highlighted a concern, "*He could have told me what a microphone was.*" This was an insightful comment that made me realize that it is essential to unpack difficult terms that some children might not have heard before.

Q4. Do you think the tablet/Jibo had any creative ideas?

I asked participants in both conditions if they thought Jibo had any creative ideas. 18.6% participants in the tablet-only condition, 35% of participants in the non-creative condition, and 79% of participants in the creative condition responded with *'yes'*. Hence, participants in the *creativity scaffolding* condition did perceive the expressed creativity of the robots. Some participants went on to explain why they thought that Jibo was creative. One participant said, *"Yes, he told me to make the [rover] move and can put more than one thing on the screen."* Another participant said, *"He had cool ideas like playing music. He played fun games with me and he had great ideas and he knows that he's smart."* One participant also said, "*Jibo thought that I had cool ideas, and that made me happy*", and another one said, "*Yes, he told me I can make what I want and told me my idea was great.*" Among participants that responded with *'No'* or *'Maybe'* there was typically no reasoning. One child in the non-creative solution said, *"Jibo knew what to do but he was not really creative."*

Chapter 6: Discussion

6.1. Discussion

In this work, I demonstrated how a social robotic peer's behavioral patterns can influence creativity in children in the 6 to 10 year old age group through two robot interaction patterns: *creativity demonstration*, where the robot itself demonstrates artificial creativity and *creativity scaffolding*, where the robot supports and encourages the child's creative thinking by asking reflective questions, providing challenges and positive reinforcements. I designed four game-based interactions that afford different forms of creativity as a gameplay behavior. The design of these interactions involved the design of the gameplay and the design of the robot's behaviors. The gameplay was motivated from standard creativity assessment measures and other tasks and games that afford creativity. The robot interaction patterns were derived from learning how children's interactions with their peers and tutors help them be more creative. These child-robot interactions not only serve as mediums for children to be supported for creative expression, but also playful ways of measuring creativity. In order to assess the efficacy of these interaction patterns, I conducted investigative studies with three of these game-based interactions: Droodle Creativity Game, Magic Draw with Jibo and Escape Adventure with Jibo, which afford children's *verbal creativity, figural creativity,* and *constructional creativity* respectively.

In the Droodle Creative Game, I demonstrated how artificial verbal creativity exhibited by a social robot during gameplay can be modelled by children, and in turn leads them into thinking more creatively in the context of the Droodle Creativity Game. This study involved participants playing the Droodle Creativity Game with a social robot expressing creative and non-creative behaviors. I observed that participants that interacted with the creative robot expressed more ideas, more diverse ideas, and highly creative ideas in the Droodle Creativity Game, as compared to participants that interacted with the non-creative robot. I also observed that when participants played the game with just a tablet, they tended to engage with the gameplay for fewer rounds as compared to when they interacted with the two robot conditions. However, there was no significant difference in the creativity scores in the tablet only and non-creative robot conditions. Hence, even though the presence of an embodied agent helped with increased engagement, the mere presence of the robot did not help children be more creative, but the expression of creativity by the robot was emulated by children.

In the Magic Draw Game, I demonstrated how artificial figural creativity exhibited by a social robot in a co-drawing task is emulated by children, and in turn led to their drawings being more creative as measured by the TCT-DP test of measuring creativity in drawings. Participants that interacted with the creative robot drew significantly more creative drawings than participants who interacted with the non-creative robot and just the tablet. Participants not only exhibited higher creativity, but also perceived the robot as highly creative. Participants in the tablet-only condition thought that the tablet was more creative than the robot in both the robot conditions, but they reported to have more fun with the robot conditions. This could imply that children find playing the game with the robot more fun, but also have higher expectations of creativity from the robot than the tablet.

Hence, through these two studies, I could verify my first hypothesis, that children can model a social robot's verbal and figural creativity.

In the second investigation involving WeDo construction kits, I demonstrated how a robot offering *creativity scaffolding* can have a positive affect on children's creativity. Scaffolding was offered in terms of asking reflective questions, challenging the participants, and providing positive reinforcement in addition to the positive affect displayed by the robot. Participants were tasked with constructing and programming a rover and then exploring how to make the rover do different things. Creativity in this task was measured by the ideas that children came up with for the rover, the number of different tools (programming bricks) they used, and how unique their ideas were. Children interacting with the robot that offered *creativity scaffolding* scored significantly higher on the number of different ideas and different programming bricks used. They also scored higher in the uniqueness of their ideas, however, that difference was not statistically significant. Children interacting with the scaffolding robot thought that robot had more creative ideas and was more helpful to them. They had some idea about how to improve the scaffolding, such as, having the Jibo screen display visuals while Jibo explains a task, or explaining what some complex terms meant. Hence, through this study, I could partially verify my hypothesis, that children are more creative in the presence of a robot offering *creativity scaffolding*.

Hence, I could establish evidence that children can learn creativity from a social robot by emulating the robot's creative behaviors and by the robot scaffolding their creative learning. I provide evidence that social agents can influence children's creativity. The positive effect of the robot's creative behavior on children's exhibited creativity in gameplay informs the design of pedagogical embodied tools to foster creativity. Previous work has discussed how advancements in Creativity Support Tools (CSTs) can help foster creativity in children [38]. Previous work has also discussed how adults interacting with a social robot that scaffolds for creativity enhance creative thinking [24]. This is the first work that demonstrates how autonomous social robots expressing creativity can be modelled by young children during play.

In order to understand the role of embodiment on children's creativity, I also ran randomized controlled trials between the non-creative and tablet only groups. In the Droodle Game, children engaged with the robot for a longer time than they did with the tablet. Similarly, in the Magic Draw Game, children who played with the robot reported to have more fun than children who played with the tablet. Hence, the social interactions and rapport building with the robot seems to have a positive effect on children's engagement and makes the experience more fun for them. In the Magic Draw Game, children reported that they perceived the tablet to be a better artists, even though they were making the same drawings. This reveals that children have different expectations from a robot than from a non-embodied and non-social medium. I saw no significant differences in expressed creativity levels. Hence, mere embodiment with no social behaviors built to support creativity does not have a significant effect on children's creativity. While we compared the R_C- and T_C- conditions, it is also imperative in future work to compare R_C+ and T_C+ (where the tablet exhibits highly creative behaviors), in order to disambiguate the effects of just embodiment versus the effects of the social behaviors. Research is HRI has demonstrated how children are more likely to socially emulate agents that they see as more peer-like and more social. Given the potential creativity benefits of the robot's sociability, it would be interesting to compare the creative-robot and creative-tablet conditions.

In classrooms, children not only learn cognitive skills from their teachers and peers, but also social-emotional skills such as curiosity, empathy, resilience, persistence and creativity. Social robots have already found a place in education as learning companions, and have been shown to have learning benefits for young children due to their ability to facilitate personalized learning (a common struggle in large classroom sizes), and higher engagement (than non-embodied interfaces). Moreover, due to reduced hardware costs and easier availability, social robots have also entered domestic and classroom settings. There is a huge body of existing research that focuses on using social robots to enhance children's cognitive learning benefits. This thesis demonstrates how social robots can enhance children's creativity. It is imperative to think about designing these learning companion robots' social behaviors and understanding how children can emulate these behaviors. Previous studies have demonstrated how children mirror other robot behaviors such as curiosity and growth mindset. Hence, we ought to be mindful about designing technology to foster, and not hinder, positive learning behaviors. Our work demonstrates how a social robot's verbal creativity skills, figural creativity skills are modelled by children in gameplay. My work also demonstrates how a social robot's behavior can scaffold children in creative tasks. This informs the behavioral design of social robots, such that they not only facilitate cognitive gains, but also focus on creative gains in children. In the next section I outline some design guidelines for robots' behaviors in order to foster creativity in young children.

6.2. Design Guidelines

The goal of this work was to design social interactions that foster creativity in young children. The approach I took to solve this was through social robots. The interaction design was inspired from social interactions in human-human interaction that foster creative thinking. I further evaluated these interaction patterns by running randomized controlled trials with children in the 6-11 year old age group. After analyzing the results of these studies, I suggest design guidelines for designing robot interaction patterns that help promote creative thinking in classrooms and homes.

Nature of the Task

Creativity expressed during a task is influenced by several factors, one of which is the nature of the task itself. In this work, we demonstrated how play-based tasks, that involved space for creative thinking, and rewarded divergent thinking, helped children be more creative. Making game-based interactions made the tasks more fun and engaging, and led to transformative behavioral change in children during gameplay. Focusing games around creation of artifacts provides children with the space for creative thinking. For instance, each of the games involved some form of creative expression. The Droodle Game involved generation of creative speech, the Magic Draw Game involved creation of drawings, and the WeDo activity involved creation of brick models. The nature of the games was such that children could create infinite possibilities of speech, drawings or models, but are constrained by the modalities like time of speech, stroke colors, or kinds of sensors or bricks that can be used.

Diversity of Tasks

The tasks must not only be open ended but also be diverse. Different children express their creativity in different ways. Tasks can be verbal, figural, construction, musical, creative problem solving, etc. Children can express creativity through prose, stories, poetry, music, painting, construction, modeling, etc. When we deploy Creativity Support Tools in classrooms and homes, we must account for diversity in forms of creative expressions. With the advent of GANs that enable generation of different media and forms of art, these artificial generations of art with artificial embodied agents become more and more possible.

Collaboration

Among social and external factors that influence creativity, collaboration is one of the most prominent ones. While designing child-robot interactions, we must ensure that the interactions are collaborative in nature and the robot acts as a collaborative peer instead of a competitive one. This is especially imperative for creativity, since we know from the literature of creativity that competition and evaluation hinder creativity in children. I also ensured that the gameplay involved collaborative instead of competitive. The collaborative nature of the interaction was made explicit in robot speech, such as, "*Today we will program a robot together.*"

Creativity Demonstration

Children learn behaviors from social emulation. We know from previous research on social robots that children can learn behaviors such as curiosity, growth mindset, perseverance from a social robot's exhibition of these behaviors. We learn from this work that children can learn creativity by modeling a social robot's creative behaviors. We validated this hypothesis using two randomized controlled trials involving verbal creativity and figural creativity. Hence, while designing social robots as pedagogical tools, we must ensure that we program their behaviors to express creativity. This definition of creativity could differ depending on the context of that task.

Reflective Questioning

Through the scaffolding study, we learned that instructors who were controlling the robot remotely chose to use many reflective questions as robot speech prompts to provide *creativity scaffolding* to children. We observed that children that interacted with this *creativity scaffolding* robot exhibited higher levels of creativity in the task. Further, research in creativity has shown how asking reflective questions about the children's actions helps them with metacognition and creative thinking.

Challenging

Providing children with optimal challenges also encourages them for creative problem solving. In the WeDo construction activity, the scaffolding robot provided challenges to the child, such as, *"Can you think of other uses of the same sensor?"* or *"Do you think that's the best way to do it?"*, which resulted in a positive effect on children's creativity. It is also important to note that the challenges should be optimal in difficulty and context based.

Positive Reinforcement

Children in all three tasks commented how the robot said "*Good job*" or other similar positive comments after they completed the task. Positive reinforcement after creative behaviors has a very strong influence on children. Children often form relationships with these social robots and getting positive validation from them upon exhibition of creativity encourages them to be more creative.

Rapport Building

In all the game interactions, through iterative prototyping, I observed that children find the interaction fun and interesting if we begin by building a peer-like rapport and establishing common ground. This could involve encouraging dialogue such as, *'what is your name?'* or *'I like dancing, what do you like to do?'* or *'Are you excited to play this game with me today?'* Further, personalization strategies, such as referring to the child with their name, help with increasing engagement. Responsiveness by the robot during collaborative activities also help establish rapport.

Positive Affect

Finally, the creative robot in all tasks exhibited more positive affect through emotional expressions. From the literature of affect and creativity, we know that positive affect is positively correlated with creativity. While positive emotions exhibited by the robot does not directly imply that the positive emotions will be exhibited by the child also, but we know that children often emulate the robot's behavior and hence this may influence the child's affect. Hence, it is important that these social embodied companions are not only creative, but also happy.

Chapter 7 : Conclusion

This work is an attempt to promote creative learning and divergent thinking in schools. Given the value of creativity in this era of AI, I attempt to make use of AI enabled artificial embodied agents to help children be more creative. I have studied the effects of an autonomous social robot's verbal and nonverbal behavior on children's creativity as measured by three game-based child-robot interactions. I first hypothesized that children can emulate verbal creativity from a social robot. I verified my hypothesis that children interacting with the highly creative robot generated more ideas, explored more themes of ideas, and generated ideas that were more creative as compared to children interacting with the non-creative robot. I then hypothesized that children can emulate figural creativity from a social robot. I verified my hypothesis that children interacting with a creative robot in a co-drawing task produced more creative drawings than children interacting with a non-creative robot. Hence, I could verify that children emulated the robot's creativity in the Magic Draw Game. From these two studies, I could conclude that children emulate different forms of creativity (verbal and figural) from a social robot, and that *creativity demonstration* by a robot has a positive effect on children's creativity.

I designed *creativity scaffolding* interaction patterns for the social robot Jibo, which involved asking reflective questions, challenging the child's assumptions, collaborative brainstorming and positive reinforcement while children engage in the WeDo Construction Activity. I observed that these scaffolding behaviors had a positive influence on children's creativity in the task.

Social robots have been shown to be effective pedagogical agents that lead to both cognitive and affective gains in young children. Since robots are already being used in classroom settings as learning peers and personalized tutors, it is imperative to think about how these robots' behaviors can influence children's learning behaviors, such as creative thinking. I demonstrate how a robot's expressed creativity can be emulated by young children during gameplay, and how the robot's scaffolding behavior can have a positive effect on children's creativity. While designing social and embodied agents, we must not only focus on their behaviors that lead to cognitive learning gains, but also foster positive learning behaviors, such as creativity. Effort much go into designing the agents' behavior such that they exhibit creativity and scaffold the child's creativity as a peer or a tutor. Embodied AI agents have the potential to use generative networks to express different forms of creativity through generating media such as drawing, poetry, art styles, patterns, physical body movements, etc. They are also socially emotive and can express the social interactions that accompany creativity such as reflection, inquisitiveness and positive affect. This work opens up the opportunity to explore how these different forms of artificial creativity can be embedded into tools that children use, and help them be more creative.

While social robots are not the only way to provide this creativity support through behavioral modeling, they certainly are a compelling way especially given their social nature. This technology is an affordable way to scale the support, and amplify and augment personalized social interaction. I would like to call out that the purpose of this work is not to pitch robots against other media as a creativity support tool, but to reinforce that when we design robotic learning peers, we must take these creativity enhancing behavioral design patterns into account.

Moreover, in this work, I got to design delightful experiences for children where they not only learned to be creative from robots, but also genuinely had fun playing games with them. I noticed how, in pedagogical science, activities are made to look like tasks that children frequently don't enjoy. I believe we must not undermine the value of playful interactions, and how play can have a powerful impact on learning. My hope is to continue working on creative robots and form a better understanding of what it means to be creative and the social aspect of creativity, and reproduce it artificially. I aim to keep building artificial embodied agents that augment human creativity and the social nuances of human creativity.

7.1. Ethical Implications

While the benefits of robots in education have long been studied, it is important to keep in mind that the long term consequences of robots in education are not known. Classroom research has demonstrated how extrinsic factors such as evaluation, competition and unrealistic expectations can potentially inhibit creativity, instead of fostering it [50]. Hence, we must be mindful while introducing an extrinsic factor in the form of a social robot, and ensure that it does not come across as an evaluator. Previous work in HRI has observed that children emulate the robot's learning behaviors such as exploration and curiosity. We observed, in our study, that sometimes these interactions led to negative experiences. Such as, in the Droodle Creativity Game, there would sometimes be time lags in Jibo's response to the child. One participant said, *"I think Jibo is rude and talks over me."* Similarly, in the Predictive Drawing task, the game was designed to have a fixed time for drawing. Multiple children reported that it was rude of the robot to stop the round and switch to his turn when they were in the middle of their drawing. We could later fix this concern by introducing a visual timer, but these game design decisions should be taken into account while designing for children, especially with tasks involving social agents.

In the scaffolding GUI design, we provide instructors with a predictive interface that helps them scaffold the child for creative learning; however, this suggestion model also limits creativity on the instructor's part. Teaching is a very personalized interaction that changes from teacher to teacher, and in trying to make a predictive instruction software, we are removing the unique character that every teacher brings to instruction. To tackle this issue, we must also aim to build personalized scaffolding models that take input from every teacher and personalize over time in both the content and style of learning. Further, in using *Wizard of Oz* interactions, one big concern is that children form unrealistic expectations from technology such as social robots. To tackle this concern, in the study, we debriefed the students about the role of the robot. Before doing the construction activity, the researcher tells the student that they are going to be doing an activity with Jibo where they make models with LEGO and that Jibo is there to help them and they can ask him any questions. They also tell the children that Jibo is still learning and makes mistakes in hearing, and can be slower in speaking sometimes. After all the studies were conducted, the after-school instructor debriefed the students about how the robot worked, and how they controlled the robot from behind the scenes. One limitation of this study, and learning for future studies, is that the participants should be debriefed individually after each study that the robot was being controlled by a human.

It is also important to think about the ethics of behavioral assessment and standardized assessments, especially for a behavior such as creativity. Using validated and standardized assessment metrics of creativity limit the definition of creativity to narrow constraints. Children's creativity, is boundless, and contextual. A drawing can score as 'non-creative' on a metric, but might seem very creative to the child. Further, creations may lie outside of the bounds of what a test defines. Further, creativity is not limited to just creating phrases and doodles, but is reflected in all aspects of our life such as creating any media, problem solving, relationships, play, etc. When we talk about behaviors in narrow constructs, we limit the expression of that behavior to a controlled space, and this is very counterintuitive to creativity. On the other hand, if we make use of fully open-ended environments with no bounds, it is difficult to measure the transformation in behavior.

We must think about ways for preventing children from having incorrect expectations from the robot through advancing efforts in educating children about AI. Furthermore, we must think about how such interactions can create learning dependencies on robots. Previous research has demonstrated how interactions with peers and teachers can help children be more creative. This research aims to learn from and supplement this social interaction, and not hinder it. It is imperative to be mindful of social inclusivity and how we place a social robot in a classroom setting in order to not detract from student-teacher or peer-to-peer interactions in the classroom. While all these interactions currently focus on one-on-one child-robot interaction, we must make an effort towards designing interactions that involve multiple children because collaboration with peers forms a major part of creative learning.

7.2. Limitations

Through this work, I identified several limitations and avenues of improvement. Firstly, creativity is not a concretely agreed upon concept and measures of assessing creativity are still debated. It is important to note that there have been several limitations identified with standardized creativity tests such as the TTCT, especially owing to the diverse understanding of creativity [9]. Further, I define measures of creativity in each of the game tasks that are inspired from standard creativity measures, but these measures need to be validated against existing measures to establish reliability. Furthermore, it is important to identify that these robot interactions lead to an increase in creativity within the narrow constructs of these tasks, and may not scale to every creative task, or in to their life outside of these tasks. We also only explore creative behaviors such as generating droodle titles, making drawings, and constructing physical models, but there are countless ways of expressing creativity such as poetry, storytelling, painting, music, etc. This work is also limited to a narrow construct of creativity that we defined as *fluency*, *novelty* and *value* of ideation. Creativity encompasses a much wider array of behaviors that can be explored using other interactions.

There were some limitations that were specific to the nature of the interaction. For instance, in the Droodle Creativity game, even though the game is structured as a collaborative turn-taking game interaction, one participant perceived it as a competitive game, and expressed a desire to *beat* the robot. This competitive perception does not give the participant any incentive to generate more ideas, or more creative ideas as compared to the robot. To address this concern, the games designed to afford creativity while interacting with a robot must be made even more collaborative, where the players' success is co-dependent, and they do not view the robot as a competitor. In the Magic Draw game, there were sometimes delays long enough for the drawings to conflict with the child's drawings or the drawings were stopped midway which made the participants unhappy. In the scaffolding task, even though I developed a robust suggestive control software, instructors still typed out some speech commands and the delay in between the command sending and robot response would make the interaction frictional. In future work, this can be fixed by making use of automatic speech recognition to translate instructors' speech to robot speech without requiring the typing of speech commands by the instructors.

There were some limitations with the design of the studies. 12 participants who participated in the Magic Draw Game and the WeDo construction task had participated in the Droodle Creativity Game before. This exposure to the robot can lead to biasing of the results. We must also control for participants' general exposure to technology, especially social technology, such as voice agents, social robots, etc, and for participants' programming experience. Even though we trained all children equally in the visual programming interface, some children had used Scratch Jr. before, which has a very similar User Interface. Post all the studies, the students were debriefed as a class about the fact that the robot was being controlled remotely in the WeDo construction task, however, per study guidelines, participants must be debriefed individually after each study about how the robot was not autonomous. In all three studies, I compared the creative robot (R_C+), non-creative robot (R_C-), and tablet-only condition (T_C-), where the tablet-only condition behaved like the non-creative robot, only without the embodiment. However, this work is missing the creative tablet condition (T_C+), where the tablet responds with creative phrases, drawings or scaffolding prompts. In order to understand if the robot's embodiment has a positive influence on the child's creativity, I need to run a comparative study between the creative tablet and the creative robot. Hence, running a 2X2 comparison study between the robot (creative and non-creative) and the tablet (creative and non-creative) would help us understand how social behaviors play a role and how the robot's embodiment plays the role.

7.3. Summary of Contributions

In this work, I contribute to the research fields of Creativity Support Tools [43], Social Robotics [101] and Transformative Games and Stealth Assessment through games [103].

There exist several Creativity Support Tools that have been shown to enhance children's creativity, and there have been several robotic toolkits that help children express creativity through construction. This is the first work that makes use of social interactions with a social robot to help children be more creative. Social robots have had other positive affective learning gains for children, such as enhancements in curiosity, engagement, persistence and mindset. This work targets creativity as a learning behavior. We specifically focus on using the robot for *creativity demonstration*, that is exhibiting artificial creativity in play, and *creativity scaffolding*, that is scaffolding children's learning with the goal of helping them think more creatively.

I designed four play-based child-robot interactions that foster creativity in children:

- The Droodle Creativity Game
- The Magic Draw Game
- The WeDo Construction Task
- The Escape Adventure Game

The interactions involve collaborative gameplay with a social robot that encourages children to be more creative through itself modeling creative behaviors such as generating creative speech in the Droodle Creativity Game or creative drawings in the Magic Draw Game, or my offering *creativity scaffolding* such as asking reflective questions, challenges, ideas and positive reinforcement in the WeDo construction tasks. I hypothesized that these social interactions with the robots will encourage children to be more creative.

I validated my hypothesis by running randomized controlled trials comparing creativity gains between the treatment group, where participants interacted with the robot exhibiting creativity-inducing behaviors and the control group, where the participants interacted with the robot that does not exhibit these behaviors. I validated my hypothesis that both *creativity demonstration* and *creativity scaffolding* offered by the social robot had a positive effect on children's creativity. This result was replicated across three different types of creativity - verbal creativity, figural creativity and construction creativity. Further, I suggested design guidelines for robot interaction patterns that help children be more creative.

In sum, this thesis contributes the design of game-based child-robot interactions that afford creativity, provides evidence for the efficacy of these interactions and provides guidelines for designing social embodied agents to foster creativity in young children.

7.4. Future Work

This work lays the foundation of using social robots as a creativity support tool for young children and provides evidence of the efficacy. In this work, I designed game-based interactions that children participate in with the social robot Jibo. These interactions are fun creative learning tools, which in the future, can be made open source and compatible with multiple social and embodied agents, and don't need to be Jibo dependent. Hence these game-based interactions can serve as pedagogical tools for fostering creativity in classrooms and homes.

I designed a *creativity scaffolding* paradigm for the WeDo construction task. This model currently supports a partially autonomous scaffolding system, where a human controls the robot using a remote control desktop program. In the current version of the robot control interface, which lets instructors control the robot remotely, we can incorporate ASR to use the instructors' speech to control the robot's speech. Moreover, collecting more data about how instructors use the program can help us build a fully autonomous model of scaffolding. This is also a case study that serves as an example methodology for developing fully autonomous scaffolding interactions for any creative activity.

From a technical point of view, the games had some technical glitches that need to be smoothed in future developments, such as robot communication lags, app memory crashes, etc. Further, as I mention in limitations, in all the studies, I compared a non-creative tablet, non-creative robot and a creative robot. While this gives us good insight about the difference in creativity gains caused by the robot's social behaviors, in order to truly understand the role of embodiment, we must also run the study with a creative tablet condition. Hence, in the future, I plan to run the studies with another group with the tablet exhibiting creative behaviors. Another interesting evaluation study would be to see the effect of both *creativity demonstration* and *creativity scaffolding* put together in the same task. I also plan to analyze my data more to figure out other underlying patterns in data, such as gender differences, and age correlates, and if the interactions help one group more than the other.

During the studies, I also collected video data of the interactions and participants' facial expressions. In the future, I will evaluate this data to assess how children respond to the robot's cues emotionally and if the scaffolding and demonstration led to a positive affect or increases engagement. It would also be interesting to look at the correlation between expressed creativity and participants' valence. In this study, I did not do any affective analysis, but given the close correlation between affect and creativity, it would be interesting data to look at in the future. Another open question with this research is the creativity transfer from one activity to another, and even in the absence of the robot. It would be interesting to evaluate how one interaction influences children's trait creativity and that creativity is transferred to another interaction. Since I developed multiple activities in this study, I can study this transfer of learning behaviors by having children engage with one activity with a creative robot and another with no robot, and study the long-term effect of creativity inducing robot behaviors outside the context of one activity.

I designed a fourth game interaction - Escape Adventure which involves creative problem solving. I make use of fluency, flexibility, originality and value of ideas, as well as tests of divergent thinking in manipulating digital simulations of physical objects in the game. I did not evaluate this interaction and plan to do so in the future. I plan to have 4 study conditions (R_C+, R_C-, T_C+, T_C-) with the creative and non-creative robot and tablet. The creative robot will exhibit *creativity scaffolding* behaviors. I plan to run an RCT to analyze how the robot's *creativity scaffolding* influences children's creative problem solving abilities in the game.

These four child-robot interaction design patterns are neither limited to game-based interactions nor to robots. Findings from this work can be incorporated in several creativity support tools such as computer games, voice agents, tablet apps, embodied tools, space design, etc. We learn from human-human interaction and apply it to human-robot interaction, but the application of these social interactions that help children be more creative can be transferred to other tools and context.

In the future, I want to continue exploring the paradigm of creative robots and what it means to develop artificial creativity. I want to pursue fundamental questions such as, what separates creativity from randomness in creative AI, how can we improve generative models to make our robots more creative, what other forms of creativity can we exhibit besides verbal and figural, and how do children perceive a robot's creativity. I demonstrated how these interactions influence children's creativity in the task, but that does not necessarily mean that it has an effect on their long-term trait creativity. In the future, I would want to explore what the long term effect on children's creativity is, and conduct a TTCT post test to report if any long term behavioral change is observed. I also want to bring this work to children in vulnerable populations, such as children with cognitive disabilities, and use co-creating art with technology as a form of cognitive therapy. I want to develop more child-robot games, especially focused around CS and AI learning that help children express themselves creatively.

A Personal Note

My inspiration for this work is to promote creative learning and divergent thinking. I believe classroom learning in schools and universities is very structured and often stifles creativity, doing a huge disservice to children's natural creativity. While this work establishes evidence for how social robots can be used as a creativity support tool, my bigger goal is to look at how all social technology, and our social interactions with technology, can be used to foster creativity in a world where technology is so ubiquitous. I want to understand how, by continued interactions with robots, we don't end up killing our inner creativity. Further, I want to move away from the view of robots being repetitive mechanical agents, but creative and enjoyable companions. In this work, to lay scientific evidence, I make use of standardized tests of creativity, but I personally disagree with *measuring* any sort of creativity. I don't think one drawing is less *creative* than others. It might be less complex, or less humorous, or less connected, or less colorful, but every creation is creative in its own way. In one sense, tests of creativity are very counterintuitive to the concept of creativity since they try to box and define what creative behaviors are. What if the child says, draws or constructs something that your test does not define? Is that not the most creative? What if the child thinks that something they made is creative, but the standardized tests believe that it is not? Standardized tests are developed by taking many people's opinions and validating against other standardized measures. In that case, these end up being *common opinions* of what people see as creative. In that sense, it is the *typical* view of creativity, which is contrary to the definition of creativity which is coming up with *atypical* ideas. Further, measures of creativity that involve human coding are often left to perception. While one can make use of intercoder reliability to ensure validity of the codes, but in a measure such as creativity, it is problematic to call something creative only if multiple people agree with it. That is the ongoing struggle with research on creativity, and the difficulties in measuring it. Being able to create new artifacts that are separate from what existed before or are a new combination of existing knowledge or is a new application of old knowledge is what leads to innovation. I want to build interactions with technology that enable children to think outside of structured barriers and be more innovative.

Moments

Figure 51. Moments from the creativity studies

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Appendix

1. Reference for Box Plots used in the document :
    a. Y-axis
    b. X-axis
    c. Max value
    d. Upper Face
    e. Quadrant 3
    f. Median
    g. Quadrant 1
    h. Minimum value

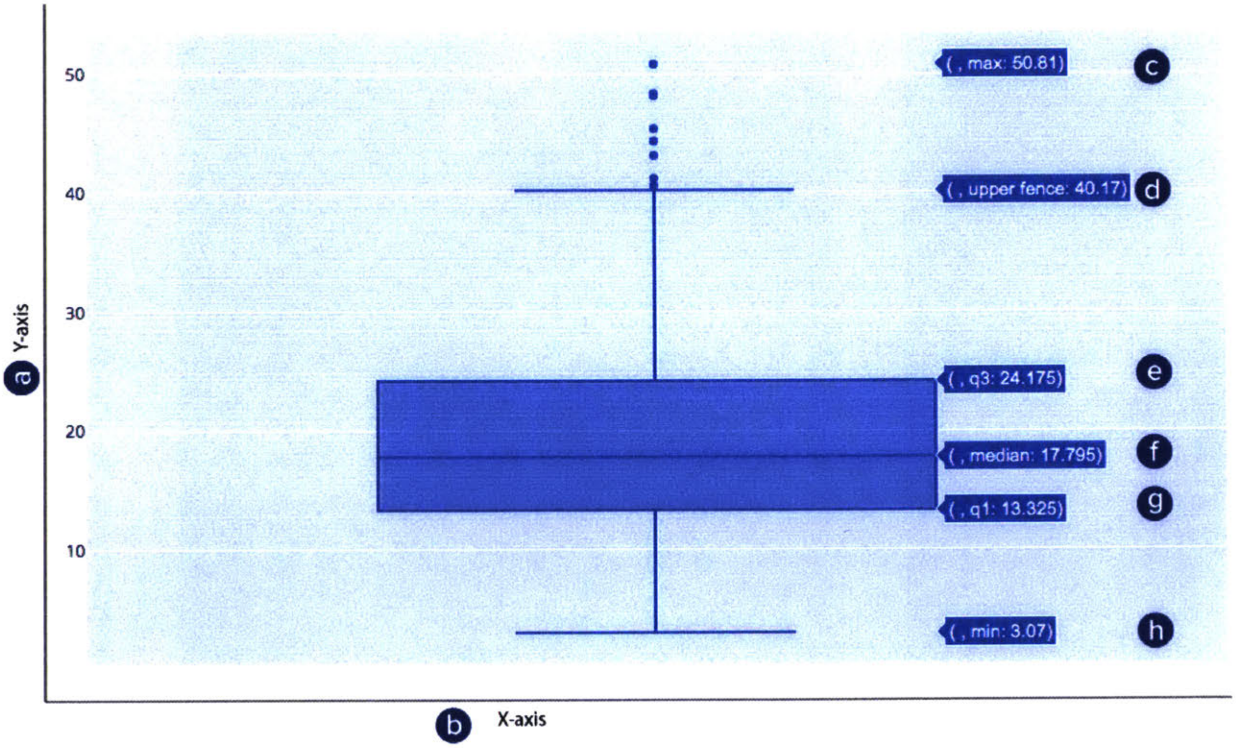

Figure 52. Reference for box-plots