ABSTRACT

Title of Dissertation: AUGMENTED REALITY SYSTEMS AND USER INTERACTION TECHNIQUES FOR STEM LEARNING

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Learning practices and crosscutting concepts in science, technology, engineering, and mathematics (STEM) subjects pose challenges to young learners. Without external support to foster long-term interest and scaffold learning, children might lose interest in STEM subjects. While prior research has investigated how Augmented Reality (AR) may enhance learning of scientific concepts and increase student engagement,

only a few considered young children who require developmentally appropriate approaches.

The primary goal of my dissertation is to design, develop, and evaluate AR learning systems to engage children (ages 5-11) with STEM experiences. Leveraging advanced computer vision, machine learning, and sensing technologies, my dissertation explores novel user interaction techniques. The proposed techniques can give learners chance to investigate STEM ideas in their own setting, what educators call contextual learning, and lower barriers for STEM learning practices. Using the systems, my research further investigates Human-Artificial Intelligence (AI) interaction—how children understand, use, and react to the intelligent systems. Specifically, there are four major objectives in my research including: (i) gathering design ideas of AR applications to promote children's STEM learning; (ii) exploring AR user interaction techniques that utilize personally meaningful material for learning; (iii) developing and evaluating AR learning systems and learning applications; and (iv) building design implications for AR systems for education.

AUGMENTED REALITY AND USER INTERACTION FOR CHILDREN'S STEM LEARNING

by

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Dedication

To my family and friends who supported me through this long journey

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List of Abbreviations

AR	Augmented Reality
CNN	Convolutional Neural Network
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
MR	Mixed Reality
OCR	Optical Character Recognition
RGB	Red, Green, and Blue
STEM	Science, Technology, Engineering, and Math
VR	Virtual Reality

Chapter 1: Introduction

Science, technology, engineering, and mathematics (STEM) disciplines pose challenges to young learners because they require understanding of scientific practices (*e.g.*, inquiry process) and concepts in addition to disciplinary knowledge (*e.g.,* digestive systems in biology) [60,197]. Children are inherently curious and have capacities to develop understanding of the world on their own. However, without appropriate intervention to foster long-term interests and scaffold learning, children's eagerness and curiosity to investigate STEM ideas may not persist [97]. Moreover, formal STEM education is often disconnected from a child's personal interests and real-world experiences, which can make it hard to understand key ideas and can negatively influence student motivation [3]. For example, children often struggle to understand abstract mathematical concepts, as they cannot see them in action nor use them in real life [27].

To address these issues, educators, researchers, and policymakers encourage incorporating innovative technologies (*e.g.*, EcoMOBILE [135], Minecraft [247]) that offer hands-on activities of problem-solving [59,237], inquiry [96], and engineering design [16]. For example, the *STEM 2026: A Vision for Innovation in STEM Education by the U.S. Dept. of Education* report [263] notes that Augmented Reality (AR) technology has the potential to transform classrooms, the natural world, and living environments into flexible learning spaces where children can develop their own STEM knowledge. The report also recognizes the potential of AR to provide situated and intelligent learning experiences, which can offer modes of learning such as scientific inquiry, “in the field” investigations, and collaboration with peers and teachers.

While an emerging area, there already exists rich albeit rapidly evolving literature on both the technical development and pedagogical use of AR learning systems. Researchers have investigated how AR may enhance understandings of scientific concepts and increase student engagement—*e.g.*, by visualizing 3D information, contextualizing the learning experience, fostering collaboration [150,220,287]. While my dissertation is inspired and informed by this literature, there are three key differences. First, my research targets young children who require developmentally appropriate practices and tools (*e.g.*, free-form design with open-ended materials) [263]. Prior work is mostly aimed at adults or high school students [12] rather than young children who have limited experience with scientific devices and practices [209]. Second, my approach focuses on personally meaningful user interaction that can promote relevance in learning. Unlike conventional AR systems supplying static learning materials (*e.g.*, displaying 3D models on a fiducial marker [83,86,142] or a place [70,135]), my research imbues AR learning content with personal data, children’s creative ideas, and surrounding environments. I hypothesize that these approaches can help children draw connections between a learners’ personal life and STEM topics. Lastly, my research explores specific AR-supported learning experiences including collaborative inquiry [15,38], design-based learning [67,105], and mathematization [54,277]. Existing AR learning systems mostly focused on providing visualizations that may help children better understand domain knowledge (*e.g.,* 3D molecular structures). Beyond providing visual information, my dissertation investigates how AR can support the educational practices that are highly stressed in STEM education—e.g., mathematization is essential to promote children's long-term engagement with math [277]).

1. 1 Research Approach and Overview

To explore the potential benefits and challenges of AR for children's STEM learning, my dissertation focuses on user interaction techniques and that can support personally relevant STEM practices. Specifically, this dissertation presents the design, development, and evaluation of three distinct AR learning systems including *SharedPhys* [138], *PrototypAR* [136], and *ARMath* [139]. These systems incorporate personally relevant information like a child's own physiology data as well as everyday objects for user interaction. With these interaction techniques, we hypothesize, children may investigate STEM ideas in their own setting, what education researchers call contextual learning [130]. For example, with ARMath, children may learn how to calculate the circular area of a cookie on the table. As another example, children may understand how physical activity affects their body by examining SharedPhys' visualization that augments the children's bodies with real-time heart rates and breathing rates.

For each system, we followed a human-centered, iterative process including: (i) designing AR user interaction and supported STEM practices, (ii) developing software systems and learning applications, (iii) evaluating the user experience—usability, preference, and learning potential—through field deployment. In the early stage of the research, we collaborated with STEM teachers and children to design user interaction and learning activity. This allowed us to understand how children would use the proposed user interface, what children could learn with AR in the formal STEM curriculum (*e.g.,* Next Generation Science Standards [197]), and identify design and pedagogical issues. With the resulting design ideas, we implemented the three distinct systems leveraging 3D graphic (*e.g.,* Unity3D [268]), sensors (*e.g.,* Bioharness for physiology [131]), and computer vision (e.g., Convolution Neural Network for object detection [119]). We also iteratively tested the systems with children to ensure the robustness and the usability. Finally, we conducted user studies in partnership with local schools, after school programs, and museums. The studies demonstrate the feasibility of our systems, identify the potential benefits and challenges of the user interactions, and suggest design ideas for AR-based learning.

Specifically, there are four major objectives and related research questions in my dissertation:

i. **Gathering design ideas of AR systems to promote children's STEM learning.** (Q1a) In what ways can AR enhance children's STEM learning? (Q1b) What are the limitations of existing AR learning tools for children? (Q1c) What types of STEM practices and lessons can be supported with AR?

ii. **Exploring novel user interaction techniques that utilize personally relevant information and objects.** (Q2a) How can children use their real-time physiological data to conduct scientific inquiry? (Q2b) How can children use paper crafts to model and experiment with complex systems? (Q2c) How can children use existing physical objects to learn math concepts?

iii. **Developing and evaluating of AR learning systems and learning applications**. (Q3a) How can we build AR systems that support inquiry learning, complex systems learning, and math learning respectively? (Q3b) In what ways can systems better support learning via visualization, scaffolding, and AI-agent? (Q3c) How do our approaches influence learning experience in terms of engagement and learning?

iv. **Building design guidelines of AR systems for children's STEM learning.** (Q4a) What are the design requirement of children and educators for such tools? (Q4b) What do we need to consider in designing AR-supported lesson plans? (Q4c) What are the benefits, challenges, and tradeoffs of different approaches in such tools?

Below, we summarize the three threads of research including SharedPhys, PrototypAR, and ARMath.

1. 1. 1 SharedPhys: Physiological Sensing, Large-screen Visualization, and Whole-body Interaction for Collaborative Inquiry

To explore user interaction using live body data, we designed, developed, and evaluated SharedPhys. With SharedPhys, children can interact physically—both explicitly via body movement and gesture and implicitly via their changing physiology. Our design study and evaluation investigated how the integrated approach can engage children in meaningful scientific inquiry (e.g., children test if their heart rates increase or decrease when they are dancing). We first conducted participatory design (PD) sessions with elementary school teachers to gather design ideas about SharedPhys interface and its learning activities. Teachers suggested leveraging physical movement, live data, and temporal and social comparison to engage children in both structured and open-ended scientific inquiry. Especially, in the open-ended inquiry, children pose their own questions about their body, design an experiment involving physical interaction and visualization to test the questions, and draw conclusions based on their observation.

Based on the results of the participatory design sessions, we developed three SharedPhys prototypes including Magic Mirror for basic human anatomy, Moving Graphs for the relationship between physical activity and physiology, and Animal Avatar for animal anatomy. Magic Mirror is designed to help understand the human respiratory and circulatory system including: the position, shape, and size of internal body parts and how the two system work together. Using a depth camera and computer vision, the system tracks users' body movement, position, gestures and augment the bodies with the users' physiological data in real-time. The system allows children to look inside one's own body and functioning organs, place individual organs with whole-body gestures, and test if an organ belongs to either the respiratory or circulatory system. Moving Graphs focuses on supporting collaborative inquiry about the relationship between physical activity and the two systems. On the large screen, the system visualizes a line graphs of real-time heart rates, breathing rates, or basic statistics. Using the graph, children can test their own inquiry questions such as "How is my heart rate changing over time?" Animal Avatar is designed to extend understanding of biological systems across animals. The system visualizes the respiratory systems of six different animals whose breathing animation is being adapted from children's live physiology. The visualization allows for role-playing the animals and cross-species comparison—making observations about similarities and differences between the animals.

To qualitatively evaluate the prototypes, we conducted six studies at two local after-school programs; 69 children (ages 5-13) and 6 adult staff participated. In the overall, the evaluation of three SharedPhys prototypes helps map out and probe an initial design space for mixed-reality environments that utilize live physiological data for inquiry-based learning. The interactive visualizations engage children's bodies through bodily actions, gestures, and exercise. In Magic Mirror, for example, children voluntarily moved their bodies left and right to view their internal organs from different perspectives or move closer to the screen to zoom-in their bodies. In the meanwhile, we observed social interaction s such as verbal communication, mimicking other's bodily movement, and encouragement. In terms of design preference, there was a clear trend toward designs that involve higher level of physical interaction. Despite the technical and administrative limitations of the sensors, our results demonstrate the rich potential of physiological sensing as a mean to interact with virtual content and promote engagement.

1. 1. 2 ProtoypAR: Prototyping and Simulating Complex Systems with Paper Craft

To explore tangible interaction via lo-fi materials, we designed, developed, and evaluated PrototypAR. The system allows children to design complex systems using paper crafts, receive feedback via AR visualizations, and test their design in a virtual simulation environment. The system is comprised of three key components including: (i) a lo-fi prototyping interface to support light and playful creation of complex systems models (*e.g.,* bike gear system), (ii) AR scaffolds to assist iterative design and aid learning, and (iii) a virtual simulation to support testing of the created models. In our co-design studies with children, we were able to understand what children like—*e.g.,* use of paper craft and personalized experiments—and dislikes—e.g., design feedback constraining creativity. Also, children suggested design ideas such as user interface to design invisible properties, in-situ testing function to verify designs early and frequently, or facilities to prompt iterative design and testing.

With prototyping interface, children can design the structure elements of a complex system and their behaviors that contribute to the system's function. The representation of structural elements includes an object's type, shape, size, position, and relationship to other elements. Behaviors are designed explicitly via printed behavioral labels; each label has a behavior name and a data field to be filled for numerical or categorical variables. In the meanwhile, PrototypAR actively tracks the work surface and offers scaffold to provide domain knowledge, guide children through the interface, or facilitate the iterative design process. At any time, the user can switch to experiment mode to make observations about how their prototypes function and why through virtual simulations. To help experimentation, the simulation environments include review panel to help comparison and selection of models and analysis panel to help interpret simulation results.

To evaluate PrototypAR, we developed three example applications—each allows children to design, build, and experiment with different types of complex systems from mechanics to optics to ecology. Then, we conducted four single-session evaluations with 21 children (ages 6-11) at two local facilities. Our findings show that a mixed reality approach—accompanied with scaffolding—can allow children to engage with modeling and experimentation of complex systems. Specifically, children approached design largely in two steps—a bottom-up step to complete a model and an exploration step to try various forms, making use of AR scaffolds as needed. They also learned about different aspects of complex systems through constructing, observing, and comparing models. This suggests that complex systems learning is approachable for young children given appropriate learner-centered tools and environments.

1. 1. 3 ARMath: Mathematizing Everyday Objects

To explore interaction with everyday objects, we designed, developed, and evaluated ARMath, a mobile AR system that allows children to discover mathematical concepts in familiar, ordinary objects and engage with math problems in meaningful contexts. With ARMath, children can explore both the mathematical composition of everyday objects—for example, the angles of a book with an AR protractor—as well as use the manipulatives to interactively solve arithmetic problems such as counting physical coins to purchase a virtual ice cream treat. Our research began with two PD sessions with STEM teachers, followed by co-design sessions with children. Teachers suggested design considerations for ARMath such as design of mathematically meaningful user interaction and opportunity to reflect on children's interactive approaches. They also enumerated design ideas including displaying equations for an on-going interaction, supporting interactive analysis of object shapes, and vocabulary learning. In the following study with children, we focused on drawing design implications asking children to use an initial prototype. The key ideas included setting up a virtual situation requiring manipulation of everyday objects and integrating AI-repairing interface to correct computer vision errors.

Informed by the PD sessions, we developed the final ARMath system—a mobile AR app—with five application modules for counting, addition, multiplication, division, and geometry. ARMath offers a four-step user experience: (i) present a virtual and mathematical situation; (ii) find specific everyday objects; (iii) interactively solve a math problem by manipulating the objects; and (iv) review a formal symbolic representation. Technically, ARMath system consists of four parts: (i) a perception engine that uses CV to recognizes everyday objects, (ii) a problem generator that creates storytelling, a math word problem, and a corresponding equation based on the perception, (iii) an interaction engine that detects interaction with physical and virtual objects for problem solving and (iv) a scaffolding engine that visualizes abstract concepts and helps with math procedures.

To understand how children could use ARMath and to uncover opportunities and challenges therein, we conducted a field deployment at a local children's museum; 27 children participated (ages 5-8). The study allowed us to understand how children engage with everyday objects for learning, their interaction patterns in tangible and virtual surfaces, and uncovered new opportunities of child-AI interaction for learning. Overall, children engaged with ARMath, reporting they enjoyed use of everyday objects and life-relevant interactions. Our video analysis indicates that AR scaffolds—e.g., visualizing symbolic notation or providing a virtual protractor—help children find solutions and support their sense-making efforts. While most children experienced several occurrences of computer vision errors, they seemed to understand limitations of AI technology and helped the system recognize objects better. This indicates the importance and acceptance of the AI-repairing interface to complement imperfect AI.

1. 2 Research Contributions

The dissertation results in three types of research contributions including formative, user interaction, and system contributions below.

Formative contributions include:

- Opportunities and Challenges of AR learning approaches
- Design considerations and issues related to AR for children's STEM learning.

User interaction contributions include:

- An embodied interface that senses and visualizes multi users' real-time physiological data (*e.g.*, breathing rate)
- A paper-based interface that allows for iterative modeling and testing of complex systems.
- Interactions with everyday objects to support solving mathematical problems

System contributions include:

- The design, development, and evaluation of SharedPhys that supports collaborative inquiry of human body.
- The design, development, and evaluation of PrototypAR that supports engineering design and complex systems learning
- The design, development, and evaluation of ARMath that supports contextual math learning in children's own settings.

1. 3 Dissertation Outline

The dissertation is organized around the three distinct AR systems for children's STEM learning. Chapter 2 presents theoretical grounds for our approaches and related work in AR and educational systems. Chapter 3-5 describe design, development, and evaluation of the three systems. Chapter 6 summarizes our contributions and discusses future work.

Chapter 2: Background and Related Work

The review of literature describes background and related work that is relevant to this dissertation. First, we present learning theories and practices that inform design of the three systems and their learning activity. Second, we survey existing AR-based learning systems and summarize the design space. Lastly, we describe three types of interactive learning systems that are relevant to our proposed systems.

2. 1 Theoretical Foundations

One overarching goal of this dissertation is to design AR-based systems that can support educational theories and practices in STEM learning. To that end, we review specific learning theories. We first present one education paradigm called personally relevant learning that our systems commonly focus on. We then describe four separate theories and practices that our individual systems support.

2. 1. 1 Personally Relevant Learning

My research builds on prior efforts to promote relevance in learning—how learning experiences are connected with students' personal interests, cultural experiences, real-world issues, and living environments [58]. Across a set of pedagogical theories that emphasize relevance such as personalized learning [81] and project-based learning [246], the shared idea is that increased relevance can motivate students to investigate ideas and increase knowledge gain. For example, Hulleman *et al.* [120] provides empirical evidence of how increased relevance can enhance student's motivation in science and academic performance [120]. In a randomized field experiment with 262 high school students, the researchers found that students gained both interest and performance in science through making connection between science materials and their lives. Similarly, mathematics education research has placed great emphasis on developing and applying instructional strategies to connect mathematical topics in the curriculum to the real world [87,244].

Because a key focus of AR technology is being aware of and responsive to the user context such as objects, user behavior, and places [98], there is rich potential to make learning experience more relevant. For example, Chiang *et al.* [50] conducted a comparative study between AR and non-AR mobile apps examining relevance of the learning tasks and materials; 57 students (ages 9-10) participated. The experimental group who used the AR app gave significantly higher ratings to relevance of their learning than the control group, appreciating the immediate access to information based on students' location and contexts.

Of course, AR by itself does not guarantee relevance in learning. For example, Di *et al*. [66] studied how AR-based learning influences student attention, satisfaction, and relevance with comparison to slide-based learning materials; 69 middle school students (ages 13-16) participated. While students showed significant improvement in attention and satisfaction for AR instruction, there is no difference in relevance of the learning experience. Student might have felt the content of AR is not relevant to their interests as the AR learning content does not offer contextual information that would respond to students' behaviors or interests. This study indicates the importance of connecting AR learning content and user contexts to promote relevance of learning.

2. 1. 2 Computer-Supported Collaborative Inquiry Learning

Computer-supported collaborative inquiry learning is characterized as the practice of conducting scientific inquiry [217] with a computer supported collaborative learning platform—a digital environment to facilitate the sharing and creation of knowledge through peer interaction [164,226,257]. In scientific inquiry, students act like scientists to study the natural and physical world applying specific skills and processes of inquiry: posing research questions, designing needed investigations, conducting and analyzing experiments, and reporting their findings with peers and teachers [148,216,274]. In doing so, students can acquire knowledge, learn inquiry skills and processes, and develop attitudes and values essential for science.

The National Science Education Standards (NSES) [56] suggests five essential features for inquiry teaching and learning, including:

1. Engaging in scientific questions (*e.g.,* posing personally meaningful questions),
2. Using evidence in responding to questions,
3. Formulating explanations
4. Connecting explanation to scientific knowledge
5. Communicating and justifying explanations.

However, integrating inquiry-based lessons in school is challenging due to lack of teachers' pedagogical skills, classroom capacity (*e.g.,* limited time and materials), and difficulty in connecting formal curriculum and inquiry [3,126,173].

Recent work suggests using computer tools to support inquiry learning for two reasons [15,113,116]. First, digital tools can help students follow specific inquiry processes such as constructing hypothesis, planning experiments, and acquiring and visualizing data. Second, the digital tools can support self-regulated learning where students can access information and hints via the tools on their own, positively affecting student motivation. Relatedly, Quintana *et al.* [216] developed a software design framework that summarize key features of software-based scaffolding to facilitate inquiry learning including i) using representations to reveal important properties of underlying data, ii) providing structure for complex tasks, and iii) embedding expert guidance about scientific practices.

The central pedagogical approach adopted in SharedPhys is collaborative inquiry learning where students work together to pose questions about human body, design and conduct experiments, and evaluating the results. Specifically, SharedPhys is designed to support *authentic inquiry* [51,243] by using learners' live physiological data, *collaboration* by simultaneously acquiring and visualizing multiple users' data, and *scaffolding* learners by embedding scientific explanations along with interactive graphics.

2. 1. 3 Complex Systems Learning

Complex systems such as combustion engines and the human body are made up of interrelated components that interact to form a holistic, interdependent system [9,94]. Despite their pervasiveness in everyday life, complex systems are challenging to learn and to teach [57,125]. Prior work has shown that students struggle to understand how individual parts of a system affect the system's operation as a whole [205,225,282], narrowly focus on visible aspects like a system's structure [114], and have limited access to real examples that could affirm or contradict their understanding [11,57,125].

To promote learners' understandings of complex systems, we leverage the *Structure-Behavior-Function* (SBF) framework [94,114], which breaks complex systems down into three parts: *structure*, elementary components and their relationships; *behavior*, the interrelated dynamics of each structural component and how they work individually and together; and *function*, the purpose of the system as a whole or a structure component. For example, within the complex system of a camera, the lens has a cylindrical *structure*, its *behavior* is focusing light rays at a focal point, which *functions* within the camera to adjust zoom-level and create clear images.

PrototypAR combines the SBF framework and *Constructionism*—a pedagogical theory that positions learning as an experiential process that is heightened when learners are building physical artifacts such as machines and games [112,201]. Through creating and presenting physical artifacts, learners can communicate their ideas with peers, ask questions, and receive feedback, which contribute to intellectual and social development [134]. This is particularly effective for science learning as constructed physical artifacts can serve as evidence for scientific explanation and justification [146]. Given capabilities to experiment with created artifacts, further resources on related science concepts and principles, and supports to encourage connecting scientific ideas with design decisions, learners can have more opportunities for engaging in scientific discussion and inquiry. Informed by this, the design of *PrototypAR* centers on providing a tangible design interface along with a testing environment to support rapid creation of scientific artifacts, iterative testing and refinement, and experiments with user-created artifacts. Especially leveraging AR, PrototypAR scaffold learners through AR prompts to bridge knowledge gaps, address problems in the user's design, and help manage design tasks.

We posit that PrototypAR's approach would promote an understanding of structure because children construct paper-based models of the individual components of a complex system (e.g., bike gears). Furthermore, the AR approach is situated to facilitate *behavior* understanding, as the augmentations show how individual components work. Finally, the virtual experiment promotes functional understandings as the digital system can simulate the effects of individual component designs on the entire system and demonstrate those effects in concrete ways that resonate with young children (e.g., bike races).

2. 1. 4 Mathematization

Recognizing and applying mathematical ideas in everyday life—*i.e.,* mathematizing the world—is critical in math education [153,238,277]. Prior work has shown that the mathematization process can deepen conceptual understanding and promote long-term engagement [200,231]. ARMath supports life-relevant mathematics learning by building on current mathematization practices in formal and informal learning environments.

In formal learning environments, teachers use several material and instructional approaches including: math word problems that illustrate realistic contexts [279], life-relevant references that directly exemplify mathematical concepts [87], and hands-on activities to actively discover math concepts [280]. ARMath builds upon these learning approaches by integrating virtual agents, storytelling, and interactive problem-solving with everyday objects to help motivate and contextualize math learning.

Children's mathematizing experiences also emerge during their play at home [5,273] such as when they create patterns with construction blocks or count their toys. In these informal settings, prior work suggests learners benefit from: (i) directing attention to mathematics during real-life activities [245]; (ii) adult intervention to scaffold learning [177]; and (iii) exploration through unstructured manipulation of objects [41]. Using these attributes of informal learning environment, ARMath integrates explicit math tasks (*e.g.,* drawing a shape, counting) and computer-mediated scaffolds that help understand abstract concepts.

While prior work suggests that AR-based math tools support active and social learning via rich information [18,142], little work thus far highlights the role of AR in supporting mathematizing experiences. Prior work mostly focused on interactive and immersive visualizations, suggesting their benefits of enhancing conceptual understanding of 3D spatial problems [141,142], dimensional analysis [75], or non-numerical magnitude [18]. Only a formative study by Bujak *et al.* [37] suggested the potential of AR to support mathematical discovery in the learner's own environment. Building upon this, ARMath focuses on utilizing physical environments, including physical objects and their mathematical or life-relevant attributes, to blend mathematical ideas and skill into everyday experiences

2. 1. 5 Embodied Learning

The role of the body in cognition has recently drawn increased attention in HCI [14, 28, 47] and the learning sciences [26, 33, 40]. This *embodied* perspective asserts that human cognition is deeply rooted in the body's interaction with the physical world [56]. Researchers have explored different forms of embodiment from using the hand as a mnemonic device [66] to using the entire body, often metaphorically through role-play, to represent molecules [63], electrical charges [68], or even CS concepts [3].With new body tracking technologies, these activities are increasingly computationally augmented— often forming a type of *mixed-reality environment* ("*the merging of real and virtual worlds*" [45]). With *Participatory Simulations* [11, 12, 15, 29], for example, learners become elements of a simulation via computer-augmented role-play.

With SharedPhys, the body is both the primary form of interaction as well as the topic of inquiry. Prior work suggests that these computer-mediated, whole-body interactions can promote and support engagement [2,228], immersion [251], sensorimotor development [151], social interaction [214,251] as well as learning (see [152] for a review). Most closely related to our work are the tools *STEP* [64] and *SMALLab* [26,129]. Both use body-tracking cameras and large-screen displays to support collaborative, embodied learning activities. Controlled evaluations of two SMALLab designs with high-school students showed greater learning gains compared with conventional instruction [129]. While highly related, SharedPhys is different in that it fluidly integrates body tracking *and* physiological sensing with a large-screen display enabling new types of embodied activities. For example, children can become body organs or even other animals (*e.g.,* grasshoppers, fish), which react not just to their movement but also their changing physiology.

ARMath also leverages the embodied nature of learning. Theories of embodied cognition highlight the role of the physical body in learning and communicating about mathematics [117,286]. For example, researchers have designed Kinect-based embodied learning systems to support topics such as counting [233] and proving [193,275], and investigated how touchpad interactions with math simulations support learning [53]. ARMath builds upon these embodied approaches by blending physical and virtual objects that are manipulated by the children's hands.

2. 2 AR Learning Systems

My dissertation builds on prior research in HCI and education technology that introduce AR-based interactive systems for STEM learning and investigate educational opportunity and challenges of such tools. Based on a survey of existing work, I first present the design space yielding six types of design dimensions: display medium, user input method, visualization purpose, instructional approach, flexibility of content, and source of scaffold. Then, I highlight user interaction techniques that are most relevant to this dissertation. Finally, this sub-section culminates in a summary of educational evaluation of AR-based learning detailing what aspects of AR are beneficial or challenging for children's learning.

2. 2. 1 Design Space

To better understand the area of research on AR-based learning tools, I developed a taxonomy of design dimensions along with existing examples. In reviewing prior research on AR technology [24,43,150] and AR for learning [12,47,70,227] more specifically, I synthesized six design dimensions, which encompass both the *technical* and *educational* aspects of AR learning systems. For example, *Visualization Purpose* refers to the role of AR visualizations in learning; AR visualization may supply 3D visual information of complex molecular structure or enable online discussion via an AR chat box. *Construct3D* [142] and Augmented *Chemistry* [83] provide *3D visualizations* to promote spatial understanding of abstract concepts (*e.g.*, geometry shapes) and invisible objects (*e.g.*, molecular structure). Chiang *et al.* [50] allows learners to exchange ideas, *collaboration* in this case, related to an object by leaving and reading comments in the registered chat box. Table 2.1 describes the entire design dimensions.

Display Technique: type of AR display
• Individual – stationary display (*e.g.*, monitors [92,227]) • Individual – mobile display [10,50,135,256] • Individual – immersive display (e.g., HMD [6,142,248]) • Shared – designated screen [74,143] • Shared – projection on the environment [61,78,86,210]
User Input Method: object or information that controls interaction
• Tangible - markers (e.g., fiducial markers [61,142,143,227]) • Tangible - domain-specific objects (e.g., lab devices [6,86,248], tangible artifacts [78]) • Tangible – free-form materials (e.g., clay, 3D fabrication [92]) • Tangible – everyday objects (e.g., bottles and cans [111]) • Body - Body shape and posture [138] • Body - Movement [74,210] • Body - Hand Gesture [154] • Body - bodily data [138] • Location – GPS and proximity to a spatial anchor [135,145]
Visualization Purpose: how AR visualization contributes to learning
• Supply 3D information [92,142,143,248] • Provide guidance and feedback [6,10,278] • Enhance presence and immersion [210]

• Provide multiple representations [50,61,78,86,227] • Support collaboration [50,142] • Facilitate a learning activity (e.g., dialogues [256])
Instructional Approach: structure of learning activity
• Observing 3D manifestation [92,142,248] • Problem-solving [10,278] • Simulation-based experiments [61,74,78,86,143,227] • Hands-on activity (e.g., role play [74], game [210,256])
Flexibility of Learning Content: what learning content adapts to
• Fixed across users and environments [92,227,248] • Responsive to user behavior [61,74,142,143] • Responsive to surrounding environment [256] • Controlled by instructors
Source of Scaffold: who or what scaffolds learning
• None [61,74,227] • Peers and instructors [143] • System [10,137]

Table 2-1: The six design dimensions of the AR learning systems design space.

To attain my research goal *iv. Building design guidelines of AR systems for children's STEM learning in life*, my dissertation explores the design space examining benefits and issues of diverse approaches therein. Specifically,

- I developed and evaluated *SharedPhys* that instantiates a combination of properties including *shared – large screen* for display medium, *bodily data* for user input method, and *supply 3D information* for purpose of visualization.
- *PrototypAR* probes into the approaches of *design materials* for user input method, *simulation-based experiments* for learning activity, and *system* for source of scaffolds.
- ARMath explores tangible – everyday objects for user input method, problem-solving for learning activity, and system for source of scaffolds.

In addition, formative studies with teachers and children gather feedback on the design attributes, summarizing their perceived benefits and challenges for learning.

2. 2. 2 User Interaction

To provide interactive and contextual learning experiences [130], AR learning systems such as in physics [74,141], chemistry [82,92,253], and electronics [71,121,179], generally employ one of three interaction approaches including:

1. *Tangible objects* such as fiducial markers [61,227] or fabricated models [92] that allow for direct manipulation of virtual content.
2. *User's bodily action* such as hand gestures [154] or whole-body movements [74,210] that can represent spatial structure or dynamic behavior.
3. *Locations* based on GPS data [50,135] that present location-specific virtual content or learning activity.

Because my dissertation explores interaction techniques using whole-body and tangible objects, this sub-section introduces relevant approaches and situate my proposed techniques within them. Specifically, *SharedPhys* combines whole-body interaction with physiological sensing. And, *PrototypAR* and *ARMath* take tangible approaches using everyday objects and craft materials respectively.

Whole-body Interaction

My approach leverages embodied interaction such as using the user's movement and gestures in an immersive learning environment. Recent technical advances in camera and human-body recognition technologies [23] lower barriers for employing embodied interaction, not requiring additional devices attached to the user's body. This enables a type of embodied learning where students use their bodies to construct simulations of difficult science concepts and conduct inquiry activity. The AR environment provides real time feedback and visualizations, upon students' bodily action, that help leverage their embodied understandings to enhance understanding of abstract concepts.

Role-play is just one method of many to involve learners' bodies actively in classroom learning. In the context of digitally-augmented environments with large displays—our focus—recent work includes *EvoRoom* [175], *UniPad* [149], and *SynergyNet* [185], all which explore combining whole-classroom, large-screen shared displays with individual or small-group interactions on tablets or multi-touch tabletops. There exists work using a single, large-screen display and physical gestures/movement to support collaborative, embodied activities, as SharedPhys does.

For example, in *Learning Physics through Play Project* [74], student can collaboratively construct a Newton physic simulation by using bodily movement and their locations in the classroom. With *STEP* [64]—using a Microsoft Kinect to track multiple bodies, students act like water particles seeing their bodies augmented with the particles on a large screen display. While highly related, *SharedPhys* is different in that it fluidly integrates body tracking *and* physiological sensing with a large-screen display enabling new types of embodied activities, for example, children can become body organs or even other animals (*e.g.,* grasshoppers, fish), which react not just to their movement but also their changing physiology.

Tangible User Interaction

A common user interaction approach is called Tangible User Interface (TUI), which supports interaction with digital content through manipulating tangible proxies (*e.g.,* fiducial markers [82,121,141,142] or experimental tools [86,253]). With computer vision-based object tracking techniques, the AR systems register 3D objects to the proxies. Then, the user can interact with the virtual 3D objects via directly manipulating the proxies. This technique is widely employed by topics that emphasize spatial perception such as geometry or molecular structure. For example, In *Construct3D* [142], teachers and students construct virtual 3D geometric models in an augmented classroom using 3D markers. Observing and manipulating 3D geometric models in the immersive environment, students can better understand shapes, spatial relations, and orientations of 3D geometry. Augmented Chemistry [82] allows students to construct virtual molecular structures by manipulating physical cards of elements, rotation, and functions. Students found the system helpful for navigating 3D structure of molecules and memorizing the structures.

With PrototypAR, I explore using craft materials for tangible interaction — which are already familiar to children. I envision this approach is particularly effective for *simulation-based experiments*. Children, as young as four years old, can naturally engage in an iterative "Make-Evaluate-Make" design model [128] using their prior experience with design materials. Unfamiliar materials such as computer-based modeling tools can pose challenges to children, as they were not capable of planning design ideas. Craft construction using paper or clay can facilitate externalizing children's ideas and understandings [181], which can be preferred by children than sketches [276]. With PrototypAR, which supports paper-based modeling of complex systems, we investigate how the tangible interaction can engage children in engineering design practices and complex systems learning

ARMath is distinct from prior work in that it uses everyday objects as physical proxies to make learning experience more relevant to children's personal interests. The tangible objects used in existing AR systems are mostly fiducial markers or custom artifacts that children hardly find in life or perceive as meaningful. I draw inspiration from the work by Bujak *et al.* [37] that suggests integrating personally meaningful objects into AR learning systems, such as allowing for using children's own marbles, could heighten learner motivation. ARMath's approach to support tangible interaction with everyday objects is not new. The physical surrounding of the user—such as physical objects and a place—has been considered as an important context that the AR system should adapt to [18]. Recent work in AR and VR user interface demonstrates how such interaction can enrich haptic experience [20] or controller interface [19,40]. For example, Henderson *et al.* suggests affordances of physical objects already existing in the user environment to improve hand gesture input and provide tangible feedback to the user, which contributes to the task performance. Hettiarachchi *et al.* demonstrates techniques to augment everyday objects with the virtual model. However, little work has investigated how interacting with physical objects in life can be used for learning.

2. 2. 3 Learning Affordances

Following the early research on AR learning tools that demonstrated its potential to support learning in various STEM disciplines such as physics [141], chemistry [82], electronics [121], and math [252], there is considerable research on examining learning affordances of AR learning tools. Though prior efforts are limited to its use in formal learning environments such as school, the literature provides useful knowledge and insights into the design space that I will address in my dissertation.

The learning affordances of AR systems are mostly derived from its integration of real world and virtual content. These include: (i) supplying additional information via real-world annotation (*e.g.*, superimposing a graph of velocity on tops of a moving ball [127]); (ii) visualizing otherwise invisible phenomena to improve visual and spatial perception of target scientific phenomena (*e.g.*, superimposing magnetic fields on real magnets [180]); (iii) enabling inquiry activity by augmenting objects or landmark with scientific data (*e.g.*, collecting environmental data in the wild [135]); and (iv) increasing learner's presence and immersion to encourage participation (*e.g.*, engaging with scientific discussion in a mixed-reality environment [50,142]bi).

While prior work has studied how AR-based learning contributes to learning gains, motivation, and collaboration [33,47,219,287], very a few researchers have investigated how it can benefit kindergarten and elementary school children. For example, case studies by Enyedy *et al.* [74] suggest that AR-based embodied modeling s can leverage children's (ages 6-8) competencies in hands-on activities (*e.g.*, role-play) for science learning. As another example, Billinghurst *et al.* [21] conducted a comparative study to understand the benefits of AR in elementary classrooms. The findings suggest that the visual augmentation can benefit children who are less able to comprehend text-based learning materials and that interactive 3D representation is effective in teaching spatial concepts. My dissertation builds upon these previous efforts by investigating how new types of interaction can support specific STEM practices.

2. 2. 4 Challenges

To inform design of our AR learning systems, I draw on prior work of identifying technical, educational, and psychological challenges of AR for learning. As a nascent area of research, only a few researchers have studied what aspects of AR challenge learning and how it could be resolved (Table 2).

Especially related to my research targeting children, Squire *et al.* conducted a case study to investigate the potential of place-based AR game—augmenting user's surrounding space with scientific data—to engage learners in scientific inquiry [256] and how learners of different ages perform; three groups of elementary, middle, and high school students participated. Though the AR game provides visual and audio information needed for scientific thinking and argumentation, the elementary participants struggled with consistently maintaining, testing, and rejecting hypotheses throughout inquiry process. Rather, the young students tend to simply put together observations to stumble on the right result often ignoring important pieces of information (*e.g.,* discomforting evidence). This indicates needs for additional scaffold to facilitate scientific thinking beyond merely providing rich information.

To examine constraints of AR, Kerawalla *et al.* [143] conducted a study with elementary students (ages 9-10) and teachers. They deployed an AR system that augments tangible fiducial markers with 3D objects at classrooms and seek to understand how children engage with the learning content and the design requirements. While teachers and children were positive about AR that supports inspection of traditionally inaccessible subject matter in real world, teachers raises a concern about the inflexibility of the content that instructors cannot control or modify learning content (*e.g.,* being unable to break down virtual content or pause visual animation). In terms of classroom management, teachers found it hard to use AR because they need to focus on technical use of AR—*e.g.,* taking care of AR camera view or preventing image occlusion—in addition to lessons and student management.

Technology
• Discomfort caused by equipment (e.g., a head-mounted display [143,290]) • Usability difficulties to manipulate virtual objects [140] • Usability difficulties to operate AR camera (e.g., visibility to the camera [143])
Learning Content
• Pedagogical decisions on distributing information across physical materials and AR [145] • Existing constraints from school environments (*e.g.,* limited time and space to use AR [189]) • Limited flexibility and controllability of the AR learning content [143]
Student's capacities
• Higher cognitive demand to interact with both physical and virtual artifacts [46,70] • Student's confusions about the mixed reality environment [145] • Differences in students' capabilities to learn (*e.g.*, literacy [84])

Table 2-2: The types of challenges children or teachers face with AR-based learning

2. 3 Interactive STEM Learning Systems

Besides the AR-based learning systems, my dissertation builds on three types of interactive learning systems including sensor-based learning system, modeling and simulation systems, and hybrid math learning systems. Specifically, SharedPhys explores a new types of sensor-based learning system that uses real-time physiological sensing for inquiry related data and computer vision-based body recognition for whole-body interaction. PrototypAR advances modeling and simulation systems by introducing paper-based prototyping and AR scaffolds. Lastly, ARMath explores the use of everyday objects in hybrid math learning systems.

2. 3. 1 Sensor-based Learning System

Originally called ‘microcomputer-based laboratories’ and later ‘probeware,’ sensor-based learning emerged in the 1980s to help children learn domain content (*e.g.,* kinematics [168], electricity [295]) and build scientific inquiry skills through sensors and interactive visualizations [265]. For example, Graphs & Tracks [168] provides a virtual environment where students can simulate the motion of a ball rolling on different types of tracks and interpret visualized data graphs in relation to the observed motion. Most prior work has focused on older students in high-school and college, with learning activities done in pairs on individual computers (*e.g.*, [234,235,259,265]). Three exceptions include a large-scale study of 100 elementary and middle school classrooms investigating temperature and pressure [294] and two studies of fourth-grade students examining graph literacy, phase transformations, and motion [65,198]. All three studies showed statistically significant learning improvements in the probeware conditions compared to conventional techniques. These gains were attributed to: (i) real-time feedback, which allowed students to make concrete connections between physical phenomena and graphical representations [65,198]; (ii) the salience of trends and events as displayed in the visualizations [294]; (iii) higher levels of engagement with science content, perhaps due to increased understandability or simply the novelty of probeware [65]; and (iv) increased levels of observation, reflection, and discussion [65]. These benefits are echoed in studies of upper grade levels as well [85,147,230,234,259,264].

Despite this long history, there has been surprisingly little consideration of physiological and wearable sensors applied to learning contexts [159]. Lee and colleagues suggest that the recent *Quantified Self Movement* and emerging commercial activity trackers such as Fitbit offer tremendous potential as learning technologies—particularly in support of science inquiry as the data is inherently personal and meaningful, the context is authentic with real-world relevance, and the body-data is plentiful allowing for rich, diverse analysis [155,158–161]. While initial studies suggest positive learning outcomes both at the elementary [159,161] and high school levels [158], the primary focus was on supporting inquiry and analysis skills (*e.g.,* graph literacy, elementary statistics). Moreover, the tasks involved pairs of students exploring retrospective activity data on individual computers. In contrast, SharedPhys explore whole-group learning activities mediated by novel interactive visualizations of real-time body-data on a shared, large-screen display

2. 3. 2 Modeling and Simulation-based Learning System

Prior educational technology aimed at complex system learning can be broken down into three approaches: (i) interactive simulation such as *SimSketch* [29] and *NetLogo* [266] that allows for testing learners' own ideas about complex systems; (ii) participatory simulation like *Hubnet* [281] and *Beesim* [206] in which learners perform the roles of elements in complex systems. and (iii) conceptual representation such as *SBFAuthor* [93] and *SBF Hypermedia* [170] that facilitate organizing and representing knowledge about complex systems. While PrototypAR build on these systems, our work differs in the use of paper craft for modeling, the integration of computer vision and AR to provide real-time scaffolding, and the focus on elementary-age learners.

To enable representing and testing ideas, existing systems offer modeling interfaces that generally follow one of three paradigms: a (1) direct manipulation interface where users drag-and-drop pre-defined primitives of a simulation [62,63,285,289]; a (2) sketch-based interface where users can draw entities to construct a system [29,283,284]; or a (3) programming interface where users specify behaviors of various types of entities [14,223,224]. While each paradigm has its advantages—for example, sketch-based interfaces can promote self-expression in modeling [29]—they also introduce challenges for novices in that each necessitates learning of application-specific modeling interfaces, limits opportunities for collaboration, and requires learners to have programming skills. Our work takes a tangible approach that uses craft materials—which are already familiar to children—to build models. We envision the tangible interface will facilitate representation of children's ideas and understandings [181] and promote collaborative learning.

Our approach for supporting tangible interfaces in PrototypAR is not new. Physical manipulatives combined with digital feedback—such as *Flow Blocks* [297] or *TimeBlocks* [107]—have been considered particularly effective for children's learning. For example, research on the *Flow Blocks* system suggests its potential to scaffold children's ability in understanding an abstract concept of causal effects. *TimeBlocks* demonstrated that illuminated interactive blocks can facilitate children's communications about an abstract concept of time. PrototypAR is distinct from prior work in that it supports free-form modeling—rather than manipulating pre-existing tangible artifacts—and provides situated scaffolds via AR—to bridge knowledge gaps and help manage modeling tasks.

2. 3. 3 Hybrid Mathematics Learning System

Our system, ARMath, builds on hybrid math learning systems that combine tangible user interface and digital feedback (*e.g.*, interactive tabletop [79]). Prior research has demonstrated the potential of this approach to enrich learning experiences with collaboration [182], tutoring feedback [190,240], rich representations [240], and physical engagement [79]. For example, Falcão. *et al.* introduces *Tangible Tens* [79] that is an interactive table with physical LEGO blocks to train basic numerical competencies such as partner number concept (*e.g.,* 6 needs 4 to be 10) and number line estimation. The quantitative study with 68 preschool children shows that the hybrid approach can increase children's numerical competency and that children can learn from system feedback. This suggests that the combination of haptic experience and digital feedback can lower threshold possibility for young children to learn mathematics. Other body of work also demonstrated the benefits of this approach for young children including: (i) improving understanding of math concepts [79,240]; (ii) bringing positive attitudes toward math [7]; and (iii) promoting engagement [4,182].

However, a system's reliance on a type of tangible objects can limit its utility. In such systems, tangible manipulatives play a significant role as concrete manifestations of abstract ideas and tools to explore and test the learner's understanding of math concepts [190]. Relatedly, learning goals supported by a system are limited by the types of tangible objects and interaction offered. For example, *Representing Equality* [162] using a tangible balance beam can only support learning of algebraic equality. *Combinatorix* [240] allows for solving and understanding probability problems through arranging tangible letters mapped to probability concepts.

To afford a range of math learning activities within a system, ARMath leverages physical objects from everyday life. Using computer vision, the system recognizes objects in the current user environment and instantiates a mathematical learning activity that can be exercised through manipulating the objects. For example, the system can recognize a set of candies on a table and present a math problem "There are 8 candies on the table. If we remove 3 out of them, how many candies are there?" Then, children can solve the problem by moving out 3 candies and counting the number of candies remaining.

Chapter 3: SharedPhys- Combining Live Physiological Sensing, Whole-body Interaction, and Large-screen Visualizations to Support Shared Inquiry Experiences.

With the emergence of body-tracking technologies such as *Fitbit* and the *Microsoft Kinect*, there has been increased interest in exploring how *embodied interaction* [68] can enable and support new learning experiences [157]. Recent work by Lee *et al.*, for example, helps demonstrate the potential of wearable activity trackers and interactive visualizations to engage children in scientific inquiry that is authentic and life-relevant [160,161]. Often citing the role of embodiment in cognition [204], others have explored utilizing the entire body through movement or gesture to support new forms of computer-mediated learning [152,157]. Though a nascent area, research suggests that these whole-body interactions can help increase engagement [2,228] and immersion [2,251], support and shape social interaction [214,251], and aid learning [152].

Building on the above work, this paper introduces and evaluates *SharedPhys*, which integrates live-streaming physiological sensors, whole-body interaction, and real-time large-screen visualizations to create a novel mixed-reality learning environment. With SharedPhys, children interact *physically*—both explicitly via body movement, gesture, and position as well as implicitly via their changing physiology. While prior work has explored body-centric inquiry (*e.g.,* [156,160,161]), the data collection and subsequent analyses are often disjoint and performed on a traditional

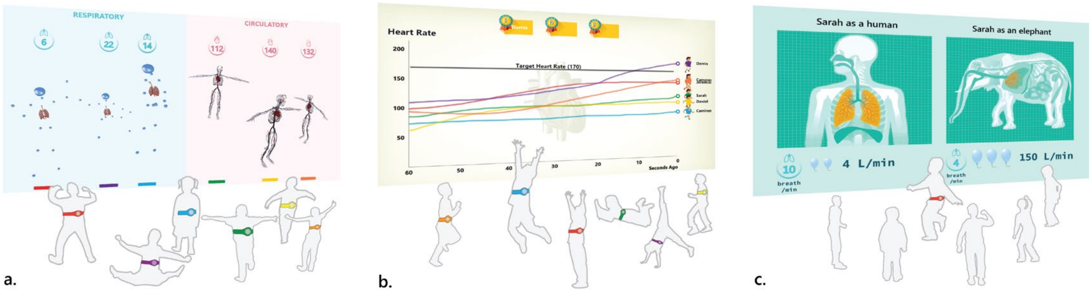


Figure 3-1: SharedPhys combines physiological sensing, whole-body interaction, and large-screen visualizations to create new types of embodied interactions and learning experiences. Shown above, our three interactive SharedPhys prototypes: (a) Magic Mirror, (b) Moving Graphs, and (c) Animal Avatar.

computer setup. In contrast, our work simultaneously involves the body in data collection, interaction, and analysis creating new opportunities for feedback loops and playful experimentation. Similarly, while recent work has explored mixed-reality environments for collaborative learning, most have utilized simulations (*e.g.,* [64,175,191]) or artificial data (*e.g.,* [213]). Our work combines live streams of *real* body-data in a shared environment. We believe this tight coupling between physical action, physiological sensing, and live visualization offers new, rich possibilities for user interaction and learning experiences.

While the primary topic of this exploration is the human body—specifically, the respiratory and circulatory systems—our overarching goal is to use the body and physical activity as an authentic platform for children to build science literacy skills and engage in meaningful scientific inquiry. As an initial investigation, our research questions are exploratory: In what ways do children interact and collaborate with real-time body data on large-screen displays? What aspects of our designs and activities seem to promote or hinder collaboration and inquiry? What are some design implications for tools that visualize real-time body data on large-screen displays*?*

To explore the potential of our approach, we pursued a three-part investigation. First, we conducted participatory design sessions with three groups of in-service elementary school teachers (*N*=20). These sessions helped to identify key characteristics for promoting learning engagement and inquiry such as *live sensor data*, *comparisons, physical movement,* and *collaborative activities*. Second, informed by these findings and by prior work (*e.g.,* [152,155,157,199]), we designed and implemented three contrasting SharedPhys prototypes and learning activities. The prototypes explore different data representations, interaction paradigms, and levels of collaboration (Figure 3-1) within our design space: *Magic Mirror* uses an augmented-reality (AR) approach to allow children to see inside their functioning bodies; *Moving Graphs* transforms live sensor data into graph form, supporting *in situ* hypothesis generation and testing; and *Animal Avatar* enables children to become animals (*e.g.,* fish, chimpanzee) whose respiratory systems respond to the children's own sensed physiology.

Finally, we conducted an exploratory evaluation of SharedPhys with six groups of children in two after-school programs (total *N*=69; ages 5-13). Qualitative findings from study sessions, pre- and post-study questionnaires, and program staff interviews demonstrate the potential of real-time body data and large-screen displays to engage children in physical interaction and new shared inquiry experiences. More specifically, our findings suggest that our integrated approach helps promote playful, data-driven inquiry (*e.g.,* rapidly iterating between hypothesis generation and testing) and alternative forms of social interaction and collaboration (*e.g.,* physical communication like body mimicry).

3. 1 Participatory Design

To help design SharedPhys and corresponding learning activities, we conducted participatory design sessions with 20 in-service elementary school teachers (19 female) enrolled in a STEM M.Ed. program. At the beginning of the session, teachers were provided with a brief introduction and then split into three smaller groups of 6-7 for participatory design. The entire process took 2.5 hrs, with 20 mins for the introduction, 75 mins for the parallel design sessions, and 45 mins for an all-group, post-session discussion. As a formative design activity, our high-level goal was to involve experienced teachers in thinking of ways that the human body, wearables, and large-screen visualizations could be used to create new learning experiences.

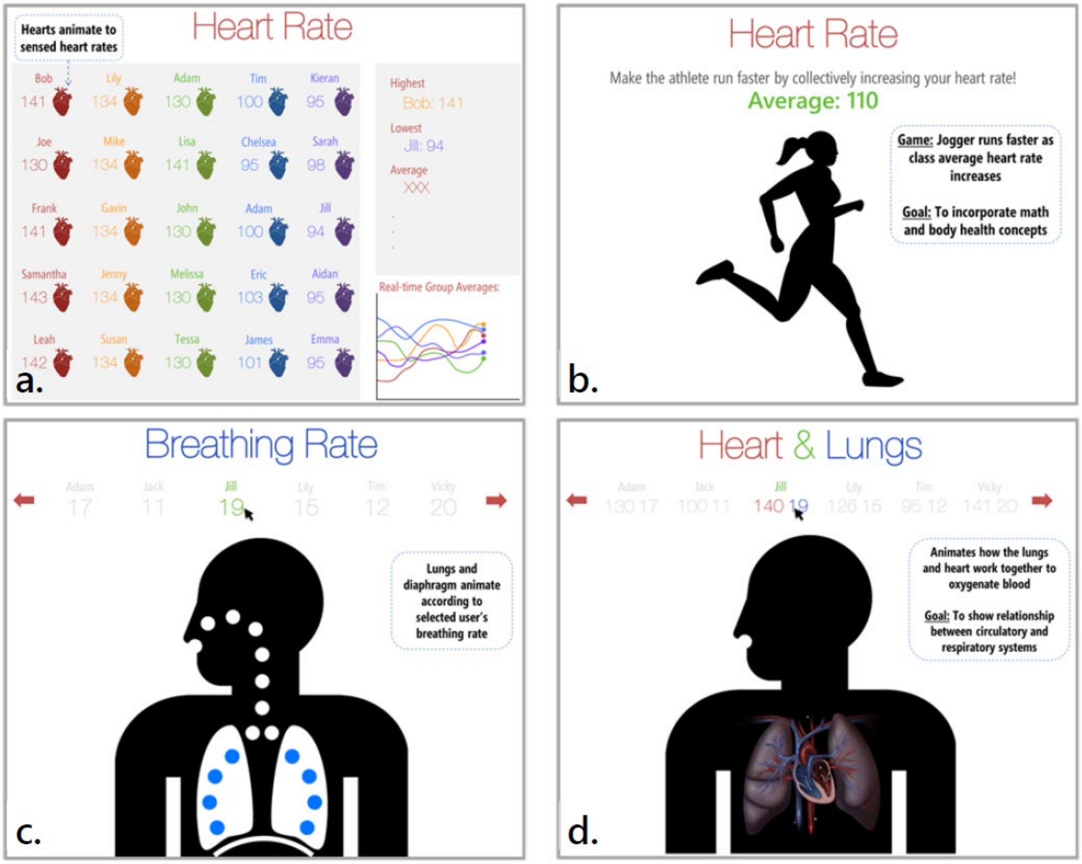
For the participatory design sessions, teachers were provided with handouts of example inquiry questions and learning goals related to our design focus, which were explicitly aligned with *Next Generation Science Standards* (NGSS) [123,195,196]. Session facilitators used these examples as prompts to help teachers develop learning activities. Teachers were also given printouts of early design mockups (Figure 3-2) and materials for sketching and arranging ideas. At the end, teachers were asked to identify opportunities and challenges for using our proposed technology.

The design sessions and whole-group activities were video recorded and the audio transcribed. For analysis, we pursued an iterative coding scheme with a mix of both deductive and inductive codes [187,236]. An initial codebook was defined based on our research goals and study protocol. Three researchers coded the sessions (one researcher per session). A fourth researcher then used constant comparison [28] to inductively identify themes within each code, first comparing within and then across sessions.

3. 1. 1 Participatory Design Ideas and Themes

Scientific Inquiry Activities. Teachers suggested a range of inquiry activities from structured, teacher-driven investigations to more open-ended approaches. For example, teachers discussed dividing the class into small groups where each group would perform an assigned activity (*e.g.,* standing, jumping jacks, running in place) and observe similarities/differences using the visualizations (similar to Figure 3-2a). Teachers also emphasized more open-ended activities such as involving children in the entire scientific process: posing their own questions, brainstorming physical activities, designing an investigation to test hypotheses using the sensors and visualizations, and drawing conclusions based on the data. In all groups, teachers mentioned inquiry activities that extended beyond a single classroom and into other classes (*e.g.,* physical education, music), recess, sporting events (*e.g.,* soccer practice), and even the home.

Body Systems and Organs. A subset of learning activities focused on helping children experience and learn about the form and function of the body. One group discussed an investigation of how individual organs react to different types of activities. The teachers would then facilitate a post-activity discussion about the causes/interactions between activities, organs, and observed physiology. Another



Hearts animate to sensed heart rates

Make the athlete run faster by collectively increasing your heart rate!

Game: Jogger runs faster as class average heart rate increases

Goal: To incorporate math and body health concepts

Lungs and diaphragm animate according to selected user's breathing rate

Animates how the lungs and heart work together to oxygenate blood

Goal: To show relationship between circulatory and respiratory systems

Figure 3-2: Four of the seven large-screen display mockups used in our participatory design sessions ranging from (a) whole-classroom visualizations of sensed heart rates to (b) target heart-rate mini-games. The bottom row shows more focused, anatomical views emphasizing (c) individual organs and (d) how organs work together. We explained that all mockups animate to sensed data.

activity involved children placing unlabeled organs onto their proper location on a model and discussing form and function related to the organs' position, size, and shape before investigating how those organs' actually functioned using sensed physiology. Finally, our teachers suggested activities to help children understand how bodies change as a result of a specific disease (*e.g.,* asthma), condition (*e.g.,* obesity), or external factor (*e.g.,* smoking, drinking caffeine).

Perceived benefits and challenges. In general, teachers were positive about utilizing wearables to aid learning: they felt that the live data, physical movement, and collaborative activities would help engage learners and that body-data could be used for cross-cutting concepts spanning topics (from math to health). Two groups also mentioned potential benefits for English language learners given the strongly visual and experiential nature of the designs. For concerns, teachers mentioned the cost, robustness, and maintenance requirements of the technology, possible issues with classroom management and setup time, and the potential for misconceptions with some visualizations (*e.g.,* if a simulation showed how heart rates increase due to smoking or drinking caffeine, children may assume the same benefits from physical activity.)

Summary. Our participatory design sessions helped demonstrate and verify teacher interest in using wearables and physiological sensing for collaborative learning. Their design ideas and activities leveraged key characteristics such as *physical movement*, *live data*, and *temporal* and *social comparisons* to engage children in both structured and open-ended investigations. Moreover, their feedback on our early mockups led directly to some final designs (*e.g.,* Moving Graphs is based on feedback to Figure 3.2a and b, Magic Mirror is based on feedback to Figure 3-2c and d).

3. 2 Three Prototypes: Magic Mirror, Moving Graphs, and Animal Avatar

Informed by our participatory design sessions as well as relevant prior work outlined above, we created an initial set of SharedPhys prototypes and learning activities—both were iterated via design critiques and pilot sessions. For our pilot sessions, we tested our designs and activities with one group of children (ages 7-11) and two groups of older students (from high school to university graduate level). Based on our pilot sessions, we developed a more proactive role for non-wearers, increased the amount of playfulness and game-like activities (*e.g.,* the addition of explicit goals and rewards), and allocated time to allow children to play and discover when first shown each prototype. Our final prototypes and learning activities are presented below.

While each prototype has a different focus, the content is interlinked and builds progressively from basic human anatomy and physiology (Magic Mirror), to relationships with health and human activity (Moving Graphs), to a broader understanding of structures and processes across animals (Animal Avatar). Due to technological limitations, classroom management interests, and information display concerns, prototypes were limited to six simultaneous users. These six users are called *players* and wear on-body sensors that wirelessly transmit physiological data in real-time. The remaining children are *reporters*, who are tasked with helping the players as well as making observations, collecting data, and providing reports to the group. Some activities explicitly pair players and reporters together.

3. 2. 1 Prototype 1: Magic Mirror

Magic Mirror is designed to improve understanding of the human respiratory and circulatory systems, including: the position, shape, and size of relevant internal body parts, the function and purpose of those parts both individually and at the system-level, and how the two systems interact to provide oxygen to the body and expel carbon dioxide (CO_2). For the respiratory system, we included the lungs, thoracic diaphragm, and the airways (the nose, mouth, trachea). For the circulatory system, we focused on the heart, arteries, and veins. While selecting an appropriate level of detail is always a pedagogical challenge, our descriptions and abstractions were informed by our participatory design sessions as well as elementary school science textbooks such as [104]. The Magic Mirror prototype itself is comprised of three separate designs/activities. All designs use a depth camera and computer vision to actively track users’ body movement, position, orientation, and gestures, which is seamlessly combined with the users’ physiological data in real-time.

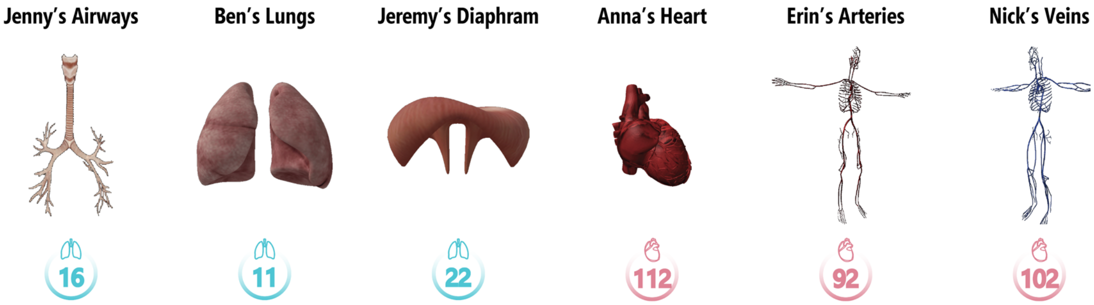


Figure 3-4: With MM2a, children become individual organs, which rotate/move with the user's body and animate based on their sensed physiology. In the actual design, each organ is shown separately along with a brief textual description.

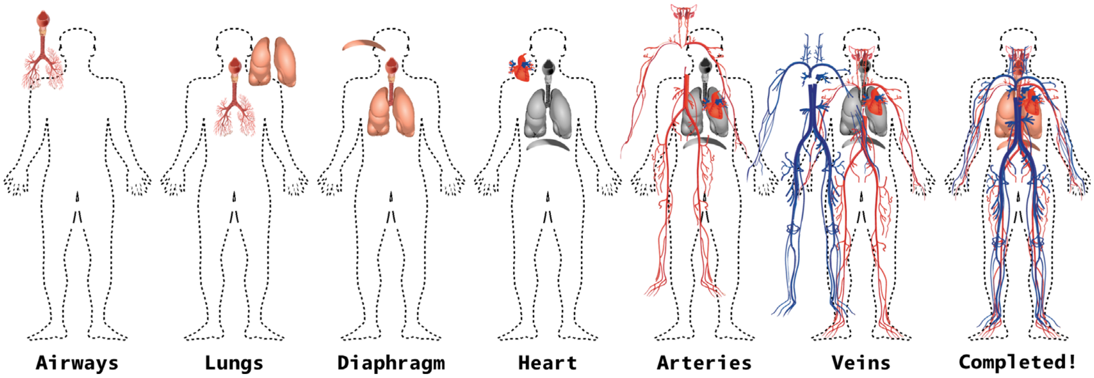


Figure 3-3: With the placement puzzle (MM2b), children move their bodies to place body parts in the correct location on an outlined human form.

MM1: Live Mirror. MM1 uses an AR approach: children are mirrored by on-screen human avatars that expose otherwise invisible body parts, which animate in real-time based on sensed physiology (Figure 3-1a). This provides the sensation of peering inside one's own body and seeing functioning organs. For example, lungs inflate and deflate and the diaphragm relaxes and contracts based on the child's sensed breathing

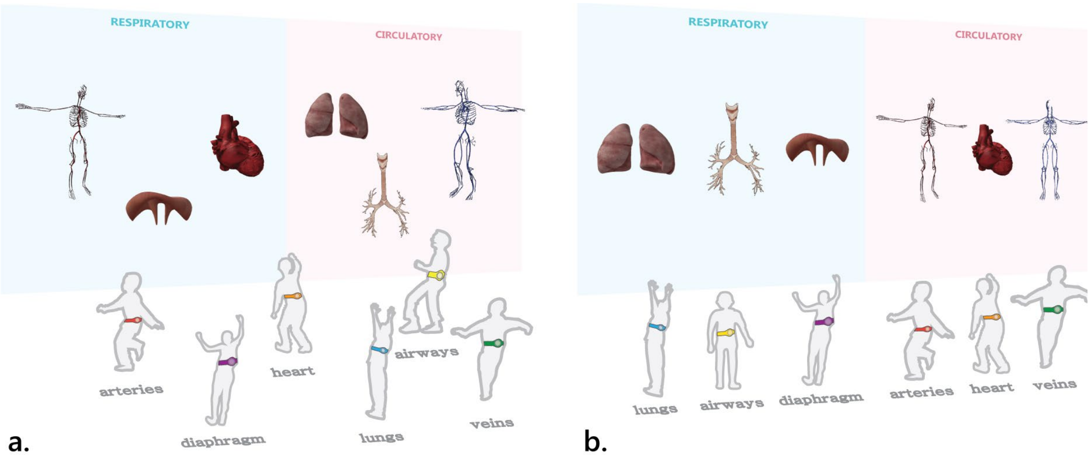


Figure 3-5: In MM3, children must move their assigned body part (a 3D model) to the correct side of the screen: respiratory (left side in blue) or circulatory (right in red). Above, (a) beginning and (b) ending game states.

rate. Because of the body's layered nature, we visualize different organs and body parts depending on the users' physical position in the interaction space—the left side is reserved for the respiratory system and the right for the circulatory system. Above each avatar, a number and graphic shows the current breathing or heart rate for that player. As with an ordinary mirror, users can zoom in/out by moving closer to or away from the screen and can see a different part of their body by changing orientation.

MM2: Becoming an Organ & Placement Game. In MM2, players become individual parts to better understand their role and position in the body. There are two separate interaction screens. In the first screen (Figure 3-3), the active player becomes a randomly assigned body part from the circulatory or respiratory system. This part is rendered as a 3D anatomical model that, as before, animates based on the active player's sensed physiology. To help build engagement and a sense of ownership, the body part is labeled with the player's name (*e.g.,* "*Erin's Heart*") and moves with the player's body. A textual description of the body part's function and purpose is also provided (not shown in Figure).

The second screen is a mini-game (Figure 3-4), called the *placement puzzle,* where players physically move to place their body part on a virtual human. If incorrect, an error sound plays and the player gets to try again. Otherwise, a reward animation and sound effect play, and the next player begins the first screen. Correctly placed body parts persist for all future players in the group so the body systems build up over time. After each system is built, reporters summarize their findings about each body part/organ.

MM3: Body Systems Game. Finally, in MM3, players engage in a mini-game to help reinforce and assess conceptual understandings of the relationship between organs and their respective systems (Figure 3-5). Similar to MM1, all players interact with the screen simultaneously, which is again split into halves: left for circulatory, right for respiratory. Like in MM2, players are represented as body part models that compose these two systems. The goal is for all players to move their model (by moving themselves) to the appropriate side of the screen. When all players are in the correct position, a reward animation and sound effect play.

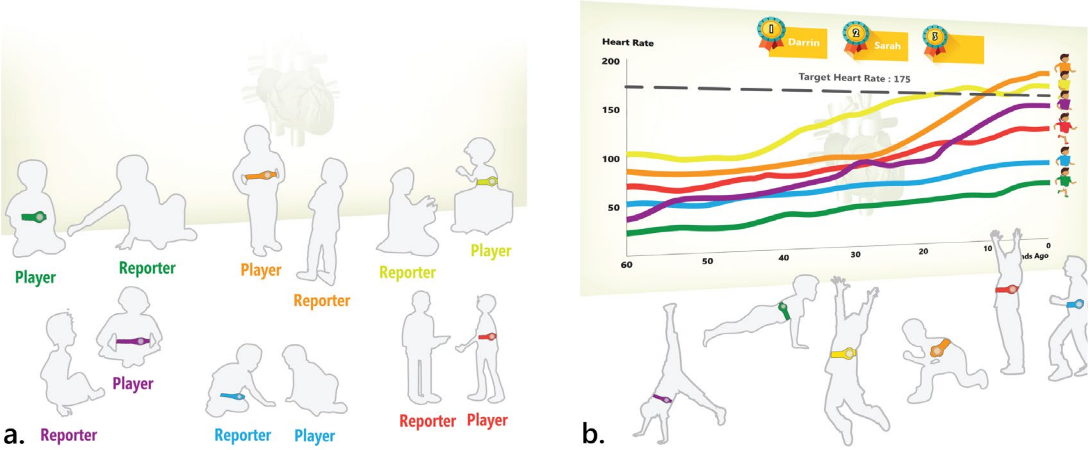


Figure 3-6: For MG1, players and reporters partner into teams to (a) brainstorm activities that affect their heart and (b) test those activities using a live heart-rate visualization. Virtual ribbons are awarded to those that reach the target rate first.

3. 2. 2 Prototype 2: Moving Graphs

While Magic Mirror emphasizes the structure, function, and purpose of the circulatory and respiratory systems, Moving Graphs focuses on the relationship between these systems and physical activity (*e.g., "What happens to my heart when I run and why?"*). Secondary goals include building STEM skills related to graph literacy and basic statistics, as well as scientific inquiry skills (making observations, testing hypotheses, and performing analyses). Moving Graphs uses a line graph to depict real-time heart rates from the six players over the last 60 seconds (Figure 3-1b). Lines are color coded by player. To the right of each line, players' names appear next along with an animation of a character running—the animation speeds up in proportion to heart rate. Moving Graphs enables both temporal comparisons (*e.g.,* "*How is my heart rate changing over time?*") and social comparisons (*e.g.,* "*How*

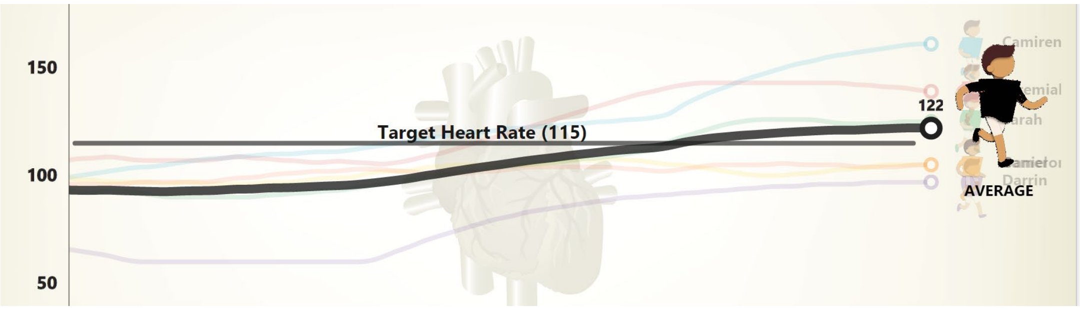


Figure 3-7: With MG2, players and reporters work together to affect the group's average heart rate represented by the thick black line and 'giant' runner. The underlying individual heart rates are still visible in the background.

does my heart rate compare to Maya's?"). It includes two activities with the same basic visualization.

MG1: Physically Testing Hypothesis. Following a brief introduction to the Moving Graphs visualization, we turn off the display, place reporters and players in teams of 2-3, and ask them to brainstorm and write-down activities that make heart rates slow down and speed up—Figure 3-6. After five minutes, each group shares one slow-down activity and one speed-up activity. Both players and reporters then return to the large-screen display to test their hypotheses. For the speed-up activities, the facilitator sets a target heart rate on the screen—roughly 20-30% above the players' cumulative resting average. Players are told to reach the target as fast as they can using their brainstormed activities. Award animations, sound effects, and virtual ribbons are provided to the first three players over the target. At the end of the activity, facilitators provide a series of provocations for discussion, such as: "*What's happening in the body to increase your heart rate? Why does this happen?"*

MG2: Basic Statistics. In MG2, we introduce the notion of *average*. We first ask the group to describe what 'average' means to them. We then show a slightly modified line-graph visualization that includes a seventh, thicker line, which depicts the real-time group average (Figure 3-7). The class is asked how to move the average up or down, and the players test their responses (*e.g., "What happens to the average if one player is physically active? How about three players?"*).

3. 2. 3 Prototype 3: Animal Avatar

Our third and final design, Animal Avatar (Figure 3-1c), is intended to broaden understanding of biological systems across animals and has only one design/activity. Players begin by selecting one of six animals: an *elephant*, a *chimpanzee*, a *fish*, a *grasshopper*, a *chicken*, or a *human child* (Figure 3-8). Players are then asked to think about and role-play their animal through movement and sounds. The prototype uses a quiz show paradigm: the display shows a question about one of the six animals and the children are asked to collectively respond. For example, "*Which animal can inhale and exhale from their nose at the same time?"* and *"Which animal uses holes along their body to breathe?"*

Figure 3-8: In Animal Avatar, players role-play one of six animals. Anatomical visualizations are shown on the screen, which react to the user's sensed physiology and are adapted into the selected animal's form.

With the correct answer, the associated player role-plays that animal to the center of the room (*e.g.,* hopping like a grasshopper). A second interface then displays a human on the left and the player's embodied animal on the right (Figure 3-1c). For both, the respiratory systems are visible and animating with the player's sensed physiology (Figure 3-9). Crucially, the animal's breathing is automatically adapted from the child's data using equations from biology and physiology [30,88,100,124,188,267]. For example, the elephant breathes at ~25% of the player's sensed breathing rate but with much larger volume [30,188]. We also display real-time breathing rate and volume data to help further enable cross-species comparison. Facilitators encourage players and reporters to make observations about similarities and differences, which are supplemented with prepared facts.

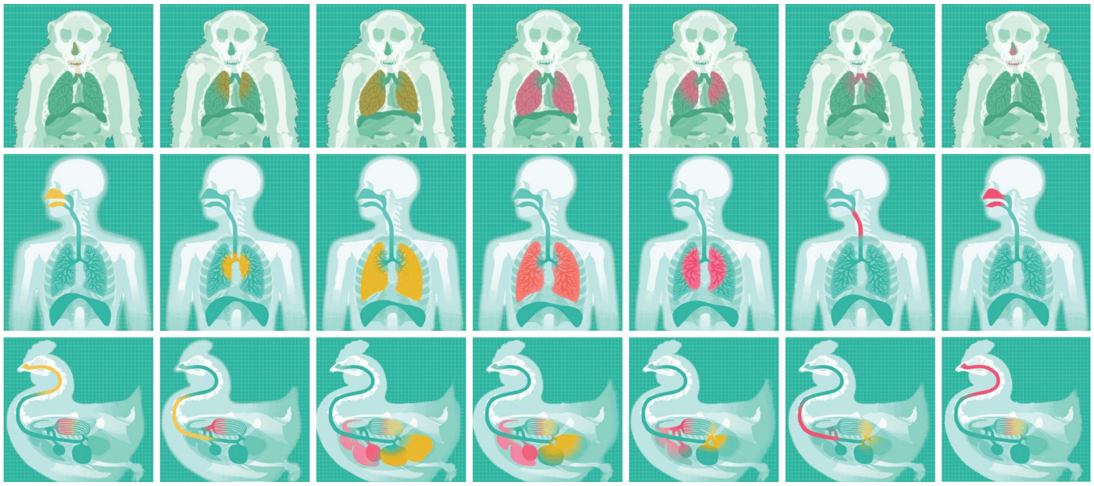


Figure 3-9: Sample animation frames (of ~23 total for each animal) for the chimpanzee, human, and chicken. The animations use color as well as organ and body movement to show breathing (e.g., lungs inflate, diaphragm contracts).

3. 3 Implementation

SharedPhys is comprised of three parts: (i) physiological and body-tracking sensors, (ii) backend infrastructure and control interfaces, and (iii) the three interactive prototypes. A single laptop is used to communicate with the sensors, upload data to the backend, control the visualizations, and project the visualizations on a large-screen display.

Sensors. For our physiological sensors, we use the *Zephyr BioHarness 3* [291], a robust body-sensing platform designed for sports training and the military. Multiple independent studies have demonstrated the BioHarness' validity and reliability for measuring heart and respiratory rates [101,144]. The BioHarness uses a flexible, chest-worn strap to sense physiological measures such as heartrate, breathing rate, ECG, and body temperature. This data is wirelessly transmitted at 1 Hz via Bluetooth. We modified the chest-worn strap to fit children's bodies. For our body tracking sensor, we use the *Microsoft Kinect for Windows v2*. The Kinect v2 is limited to recognizing six simultaneous users.

Backend. A host application written in C/C++ for Windows establishes and maintains Bluetooth connections with the BioHarness sensors, parses the BioHarness data packets, and uploads the data to a backend database. The data is shared directly with Magic Mirror via interprocess communication but via a web service for Moving Graphs and Animal Avatar. A control interface along with an instructor-facing web app were created to manage the visualization screens and monitor system health (*e.g.,* sensor connectivity).

Interactive Designs. Moving Graphs and Animal Avatar are web-based visualizations implemented in D3 (d3js.org). Magic Mirror is a standalone Windows application implemented in Visual C++ and Orge3D (orgre3d.org). The reward animations used in Moving Graphs and Magic Mirror were created in Adobe After Effects, and the sound effects are from soundrangers.com. The animal respiratory animations were made in Adobe Illustrator and After Effects based on original animations by Eleanor Lutz [176].

3. 4 Evaluation

To qualitatively explore and solicit feedback on our prototypes and to uncover particularly promising activities/designs that could be refined in future work, we conducted six exploratory evaluations of SharedPhys in two local after-school programs.

Across the six sessions, a total of 69 children participated (42 boys, 27 girls) aged 5-13 (*M*=8.8; *SD*=2.1). Sessions were roughly broken down by age, based on pre-arranged ‘teams’ at our program sites. While we did not customize our prototypes or learning activities based on age, instructors did adapt their language for younger and older groups. The average session size had 11.5 children (*SD*=3.8; *Min*=5, *Max*=17). In the session with five participants, a program staff member stepped in for the sixth player slot. Players were selected by asking for volunteers and randomly selecting three boys and three girls. Prior to the study, parental consent was acquired, including permission to take photos and record audio/video. In total, six program staff helped across the six sessions. Three had professional teaching experience. Two research team members served as ‘instructors’ during the session.

Each session lasted approximately two hours and included: (i) a 25-minute introduction with a brief overview, a pre-study questionnaire, an icebreaker, and assigning volunteers to player and reporter roles; (ii) a 15-minute setup period where staff helped players put on their BioHarnesses while reporters were assigned specific body parts to keep track of and asked to fill out preliminary notes based on current understanding; (iii) an hour session with SharedPhys; and (iv) a 15-minute concluding activity with a post-study questionnaire and snack. To gather additional perspectives, we also conducted individual, semi-structured interviews with the six staff who helped facilitate sessions. Interviews lasted ~10 minutes and were also video recorded.

3. 4. 1 Data and Analysis

We use three primary sources for our analysis: the pre- and post-questionnaires, video recordings of the sessions, and the program staff interviews. Multiple video cameras were setup in the classrooms to capture facial expressions, physical movements, and social interactions as well as interactions with the large-screen display. The pre-questionnaire contained: body map drawing activities where children were asked to draw the respiratory and circulatory systems (a standard assessment approach [89,222,271]), questions on the purpose and function of these systems and related organs, and questions that required reading/analyzing a line graph. The post-questionnaire included questions about the SharedPhys prototypes and the child's overall experience. To gain a preliminary understanding of learning potential, some pre-questionnaire questions were also repeated.

To evaluate children's interactions and engagement, we analyzed the video data and pre- and post-questionnaires. For the video analysis, we followed Chi's eight-step process [49] using a mixed deductive and inductive approach. A single researcher developed an initial codebook based on prior work in learning engagement [42,218], our study goals, and watching a single video. Three researchers then met and simultaneously coded a second video, concurrently updating the codebook. Finally, two researchers coded all six videos independently, developed summaries, and then met to discuss and co-interpret the data. A final summary with examples was also co-written. The video data was used to analyze interaction and behavioral indicators of engagement [218] such as body position, gaze, facial expressions, and verbalizations. The questionnaires were used to analyze more psychological indicators (*e.g.,* self-reported interest).

For the six staff interviews, we used an analysis similar to the participatory design sessions. An initial codebook was derived from study goals (*e.g.,* engagement, social interaction, perceptions). Two researchers independently coded all six transcribed interviews and resolved disagreements through consensus. To further condense themes across interviews, one researcher did a final, inductive coding pass using constant comparison [28]. For the body map drawings, two researchers independently coded the label, shape, position, and existence of circulatory and respiratory body parts in the pre- and post- questionnaires. In total, 68 questionnaire pairs were analyzed resulting in 3264 total codes (240 disagreements). Cohen's Kappa was used to verify high inter-rater reliability ($\kappa = 0.92$). All 240 disagreements were resolved through consensus.

Figure 3-10: (a) Zooming into Magic Mirror to get a closer look at animating lungs; (b) gesturing and shouting to help a player in the placement puzzle; (c-e) testing activity hypotheses with Moving Graphs; and (f-g) acting like a fish and a chimpanzee in Animal Avatar.

3. 4. 2 Findings

We report on findings related to physical and social interactions, the impact of games, indicators of enjoyment, reported design preferences, and learning potential as well as perspectives from the six program staff. We refer to quotes from questionnaire data as: *(PId, Gender=[Male, Female], Age, Role=[Player, Reporter]);* we are not able to attribute quotes from the videos. While 69 children participated, only 68 completed the post- questionnaire.

Physical Interactions

Our visualizations, system interactions, and learning activities engaged participants' bodies through movement, gesture, and exercise (Figure 3-10). When each design was first shown, players immediately began experimenting physically, typically before instruction. This was most prevalent in Magic Mirror and Moving Graphs. In Magic Mirror, players voluntarily moved their bodies left and right, often breaking into dance and jumping, to view their bodies and organs from different perspectives (Figure 3-10a). Players quickly discovered that they could move closer to the screen to 'zoom in' on their bodies, which created waves of back and forth movement as well as comments of delight and disgust "*Oh my gosh!*", "*Wee my head is huge! OK, now I'm getting creeped out!*" Reporters were far less physically active than players, perhaps because they were tasked with collecting observations or because of the mirrored 1:1 nature of the visualization. One exception was during mini-games where reporters would shout and gesture to help players win.

With Moving Graphs, players instantly started moving fast—jogging in place, jumping jacks—as soon as the graph was displayed. During hypothesis testing and the competitions, players were extremely focused—making very few utterances; however, reporters would shout encouragement and instruction: *"Keep going!" "Look at how high your heart rate is!" "Amanda, try push-ups!"* Compared with the other two prototypes, reporters were far more likely to engage in physical activity themselves, often matching players' movement (Figure 3-10d). When testing slow-down and speed-up activities, players would begin with the activity that s/he brainstormed with their reporter partner but then quickly switch to the activity that seemed to work best so that by the end, most players were doing the same activity.

Overall, there was less physical movement with Animal Avatar except for the animal role-play perhaps because this interface did not require explicit, computer-mediated physical interaction or because of its turn-taking nature. However, players would breathe in and out deeply or very fast to see how this would influence the respiratory animations in their animals. The role-play (Figure 3-10f and 3-10g) and tight, responsive coupling between player and animal did seem to increase engagement; however, some players/reporters seemed to lose interest when their animal was not active.

Social Interactions

We focus on two categories of observed social interaction: within-group (*e.g.,* player-to-player) and across-group (*e.g.,* player-to-reporter). Most verbal within-group interaction occurred between reporters who helped each other take notes, stay on task (*e.g.,* "*Lucas, you're the lungs!"*)*,* or repeat things that were not originally heard. In contrast, players were more focused on themselves and their live data representations. Consequently, there was less *explicit* interaction between players; however, players would interact implicitly as they observed other players' actions and their effect on visualizations, and then try to replicate them.

For cross-group social interaction, reporters were much more vocal in interacting with players than players with reporters; however, players would often respond *physically* to reporters by changing their interaction or movement. For example, in Magic Mirror, reporters proposed different movements to try in the mirror and shouted suggestions or mimicked actions for solving the placement puzzle (Figure 3-10b). In Moving Graphs, reporters would often engage in their own exercises or match their partner and would shout encouragement and suggestions (as noted above). For Animal Avatar, some players were shy about role-playing, so reporters would help make animal sounds and actions.

Games

Similar to prior work in whole-body interaction [214,228], we found that games were successful in building engagement. This finding extended even to reporters who were not wearing sensors and whose data was not being visualized. While reporters did seem less involved in some designs, their engagement often peaked during games and competitions. With the placement puzzle (MM2), for example, reporters would shout and raise their arms to help players place their body parts. The most physical activity—for both reporters and players—was during the Moving Graphs competitions. Here, all participants would engage in some form of physical exercise and experimentation even though only players' data was represented on screen.

Enjoyment

In our video analysis, we found many indicators of enjoyment from positive facial expressions and excited utterances to active attention and participation. Indeed, on the post-questionnaire, most children (91%) indicated having fun during the session. Reasons included being able to move a lot, being able to see internal parts of the body actually working, and enjoying learning about the body. One participant said "*I haven't* *had this much fun basically all summer*" (P66, M, 13, P). Of the five participants that reported *not* having fun, three were reporters and two were players. Two of these reporters stated they would have had more fun if they wore the sensor, one player indicated not liking any of the activities. The remaining two provided no explanation. As an additional indicator of enjoyment: while 39.7% participants felt that '*learning about my body and body organs*' was '*very interesting*' on the pre-questionnaire, this increased to 56.1% on the post-questionnaire.

Design Preference.

When asked to select a favorite prototype, Magic Mirror was most preferred, selected by 28 participants (41%), followed by Moving Graphs (35%) and Animal Avatar (24%). Reasons for selecting Magic Mirror, included: enjoying how it mimicked the body, its use of physical interaction, and being able to see inside one's body. For example, one child said "*I loved how it copied me"* (P36, F, 10, P) and another: "*It shows what the inside of your body looks like and how it moves"* (P37, M, 13, R). For those that selected Moving Graphs, common reasons included being able to compare heart rates, the type and amount of physical activity required by the prototype, and the competitions. For example, "*it shows the different heart rates between people*" (P30, F, 12, R), "*I like pushups and running"* (P2, M, 5, P), and "*It was fun competing"* (P25, M, 10, P). Finally, for those that selected Animal Avatar, children emphasized the comparison between animals and humans, enjoying seeing how different animals breathed, and being generally interested in animals. For example, "*it is cool seeing how* *fast or slow you would breathe as an animal"* (P59, F, 9, R) and "*it made us know [sic] that elephants breathe more air and that you breathe more when you are young"* (P12, M, 12, R).

Despite differences in age (from 5-13), we did not observe significant behavioral differences across sessions in our video analysis. However, we found that younger children (age 5-8, *N*=33) selected Magic Mirror most frequently as their favorite (51.5%) followed by Animal Avatar (27.3%) and Moving Graphs (21.2%). For older participants (age 9-13, *N*=35), Moving Graphs was most preferred (48.6%) then Magic Mirror (31.4%) and Animal Avatar (20%). However, a chi-square test comparing these two age groups ($X^2_{(2,N=68)} = 5.84$, $p = .059$) was not significant at $p < 0.05$. More work is needed to explore this trend. We also examined preference differences between reporters (*N*=36) *vs.* players (*N*=32). While players preferred Moving Graphs (44.4%) followed by Magic Mirror (41.7%), reporters preferred Magic Mirror (40.6%) then Animal Avatar (34.4%). Again, however, a chi-square test ($X^2_{(2,N=68)} = 4.84$, $p = .089$) was not significant at $p < 0.05$.

Learning Potential

Though the primary intent of our study was not to assess learning, we did compare pre- and post-questionnaire data to gain a preliminary idea of effectiveness. Participant body map scores improved between the pre- and post-questionnaires, from *M*=8.5 (*SD*=4.9) to *M*=12.0 (*SD*=7.0) out of 24. This improvement was statistically significant as shown by a paired t-test (t_{67}=4.89, p<.001)[1]. Overall, the greatest gains were observed in shape (62% of the participants), existence (60%), and position (51%). While a total of 45 participants increased their scores (66%), a surprisingly high number (28%; N=19) decreased. In examining this further, we found that a few children had done relatively well on the pre-questionnaire but did not fill out the post-questionnaire or wrote *"I don't know,"* perhaps due to fatigue.

We also assessed the five questions that were repeated on the pre- and post-questionnaires, including three multiple-choice questions that required analyzing a line graph and two fill-in-the-blank questions about the circulatory and respiratory systems. Overall, participant scores increased from $M=1.8$ (SD=1.4) to $M=2.0$ (SD=1.4) out of 5, however, this difference was not statistically significant. Most gains were on the body-system questions—29% of participants improved while 3% performed worse.

Program Staff Interviews

With regards to the perspectives and reactions of the six program staff, generally all were positive about the potential of SharedPhys to engage children in learning. Noted benefits included: the authentic connection between body data and activities, the importance of physicality and mimicry (*e.g.,* live 3D anatomical models of the body), and SharedPhys' ability to make STEM-related learning relevant and fun. For example, one facilitator, a former teacher, felt that the graphing in SharedPhys "*was*

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[1] This data met the normality assumption: Shapiro-Wilk result was W=0.98, p=ns.

very authentic… it just really made the math alive" (S5). Most facilitators emphasized the tight coupling between the physiological data and our visualizations in building engagement and relevance: "*It's one thing to show a picture of the respiratory system, it's another thing to have them see their own"* (S2) and *"The cause and effect relationship, the interactivity… all those things make much more personal education… just learning on a deeper level."* (S5). Two staff mentioned that SharedPhys was able to engage children who otherwise struggled to pay attention during prior STEM activities: "*they were on task, well behaved… that was awesome*" (S6).

When asked about player and reporter roles, most (5/6) staff members felt that it was *not* necessary for everyone in a class to wear a sensor, though they felt that everyone should have the opportunity. Two staff reasoned that players were not as focused on learning concepts as reporters. Another felt that it would be too hard to visualize more than six wearers' data at once. The one staff member (S6) who thought *everyone* should wear a sensor felt that players were far more "*involved and on task*" than reporters.

Finally, several staff members shared pedagogical suggestions and design ideas for SharedPhys, including adjusting the complexity of content based on age and developmental stage, spreading the use of the tool out over multiple days/weeks, and allowing reporters and players to more easily switch roles. Similar to our participatory design sessions, staff raised concerns about cost and durability but also the need for professional development and the overhead required to setup and use our tools.

3. 5 Discussion

This research contributes to two growing but nascent areas of research: (i) mixed-reality environments to support embodied interaction and learning [166] and (ii) body-centric technologies for inquiry [156,157]. Specifically, we investigated the potential of integrating live physiological sensing, whole-body interaction, and large-screen visualizations in a multi-user environment to support and promote new forms of interaction and shared inquiry experiences. Our findings suggest that the tight coupling between physical interaction, physiological sensing, and responsive visualizations helps promote engagement, allows children to easily explore cause-and-effect relationships, supports and shapes social interactions, and creates a fun, playful experience. As an exploratory, qualitative study, our findings also help provide design guidance and ideas for future work.

Design preferences. Children's preferences were fairly evenly split across the three prototypes, though there was a clear trend toward designs that required higher levels of physical interaction. Preferences also point to the promise of using AR for body inquiry. With Magic Mirror and Animal Avatar, for example, children liked to see avatar versions of themselves with real-time animations of functioning body parts. Future designs could include interconnections between body organs, higher-fidelity models, or other parts of the body (*e.g.,* how muscles work [186]). With Animal

Avatar specifically, children seemed deeply interested in cross-species comparisons and were struck by how their physiology manifested in other animals; however, the sequential nature of the design and lack of explicit physical interaction limited engagement. We envision a hybrid approach where children can become other animals in a Magic Mirror-like design. Finally, our findings highlight the value of games and competitions to help promote collaboration and build collective investment between wearers and non-wearers (echoing [31]).

Wearers *vs.* non-wearers. To promote equitability and engagement, we initially envisioned that *all* children would simultaneously wear sensors. As such, we were surprised to find no differences in reported 'fun' between wearers (players) and non-wearers (reporters) and that most program staff (5/6) felt that sensors for all children were not necessary. Indeed, our study identified benefits to both roles. Wearers had greater control and a more direct connection to the data, whereas non-wearers had more time to reflect, observe others, and record observations—while still engaging physically by mimicking or demonstrating suggested movements. For future designs, we recommend both incorporating activities that help children slow down and reflect on their learning [90] and allowing children to easily switch between wearer and non-wearer roles (echoing [251]'s notion of 'social balance').

Physiological sensing. While we believe there is rich potential in using physiological sensing in mixed-reality environments, sensors can be expensive and require time to put on/take off (making it difficult to switch wearers). In addition, most wearables are not designed specifically for children. We modified the BioHarness's chest strap to fit a child's body, but at least one child in each session complained of discomfort. While less invasive sensors are available (*e.g.,* the wrist-based *Fitbit Charge HR* or camera-based techniques [211]), they often provide only one measure (*e.g.,* heart rate), are less accurate, or do not provide a programming API. Future designs should consider expense, accuracy, invasiveness, and switching overhead along with user interaction and learning goals. As mentioned above, expense can be mitigated by having fewer devices and allowing children to switch.

Social interactions. Social interactions between learners are often characterized by verbal or text communication or, more recently, via digital media (*e.g.,* [175]); however, we observed important non-verbal forms as well. Leveraging whole-body interaction in the shared mixed-reality environment, children communicated with their bodies both explicitly and implicitly. Explicit communication often meant physically demonstrating a suggested activity or helping to encourage a player. More implicitly, children would observe other children's physical actions to learn new ways of interacting with the system and to gain a better understanding of their own performance. This was most striking with Moving Graphs where, by the end, most children had converged on the same one or two activities that seemed to work best. This convergence helps demonstrate the visibility of action in a shared, mixed-reality space and how social observation and modeling can potentially lead to learning.

Benefits and drawbacks. Our findings suggest that SharedPhys's tight coupling of action and visualization is approachable, engaging, and helps promote collaborative data-driven inquiry. In contrast to prior work [158,159,161], SharedPhys supports body inquiry experiences via whole-body interaction in a *shared* environment, enabling and shaping collective investigations. Still, there are challenges. First, the real-time, collaborative nature of the activities forces all children to engage at the same pace. Second, as noted previously, vigorous physical interaction sometimes limited opportunities for reflection. Third, physical, body-centric activities have the potential to raise sensitive issues such as fitness level and body shape. While this last concern did not arise in our study, future designs should consider how to mitigate this potential problem. Finally, to address issues due to the real-time nature of our approach, we suggest including complementary retrospective tools (as in [158,160,161]) for reviewing and (re)analyzing the real-time data.

Study Limitations. We deployed and studied three contrasting prototypes using a single-session study design. While useful for identifying promising activities and design elements, studying initial impressions, and uncovering usability issues, the study design is susceptible to novelty effects. The session length may also have been long for some children, who appeared to tire. More in-depth studies are necessary for evaluating longer-term usage patterns and learning benefits. Still, the combination of methods used—participatory design, tool evaluation with 69 children, and staff interviews—helps mitigate the limitations of any one technique. We are currently working with two site partners to examine longitudinal uses of physiological sensing and visualizations in informal and formal learning contexts.

3. 6 Summary

We pursued a multi-stage, mixed-methods approach to evaluating the potential of live physiological sensors, whole-body interaction, and large-screen visualizations to engage children in playful, collective inquiry. Participatory design with teachers helped (i) demonstrate and verify interest in utilizing body sensors and live multi-user visualizations to support learning; (ii) provide design and group learning activity suggestions; and (iii) identify key characteristics for promoting engagement and inquiry. The design and evaluation of three contrasting SharedPhys prototypes helps map out and probe an initial design space for mixed-reality environments that utilize live physiological data for body-centric inquiry. Our findings suggest benefits in the tight coupling between action and visualization, the social interactions afforded by a multi-user mixed-reality environment, and in the interplay between wearers and non-wearers.

In summary, our contributions include: (i) the introduction of a new mixed-reality approach that combines on-body sensors and real-time, large-screen visualizations for physical, collaborative interaction and learning; (ii) findings from our participatory design sessions and six exploratory evaluations; and (iii) design reflections and directions for the emerging areas of mixed-reality environments to support embodied interaction and learning [166] and body-centric technologies for inquiry [156].

Chapter 4: PrototypAR- Prototyping and Simulating Complex Systems with Paper Craft and Augmented Reality.

Complex systems such as combustion engines and the human body are made up of interrelated components that interact to form a holistic, interdependent system [9,94]. Despite their pervasiveness in everyday life, complex systems are challenging to learn and to teach [57,125]. Prior work has shown that students struggle to understand how individual parts of a system affect the system's operation as a whole [205,225,282], narrowly focus on visible aspects like a system's structure [114], and have limited access to real examples that could affirm or contradict their understanding [11,57,125].

To address these challenges, prior work has explored the use of interactive computer-based simulations where children can build or manipulate aspects of a system and study differences in simulated results [63,76,125,223]. This approach allows learners to interact with otherwise inaccessible complex systems [114,125], helps reveal and modify their misunderstandings [125], and improves their grasp of how a system functions as a whole [270]. While promising, existing systems are rarely designed for young children (K-5), use traditional mouse-and-keyboard interfaces that limit how models are constructed, and do not scaffold learners through the full design process—from modeling to experimentation.

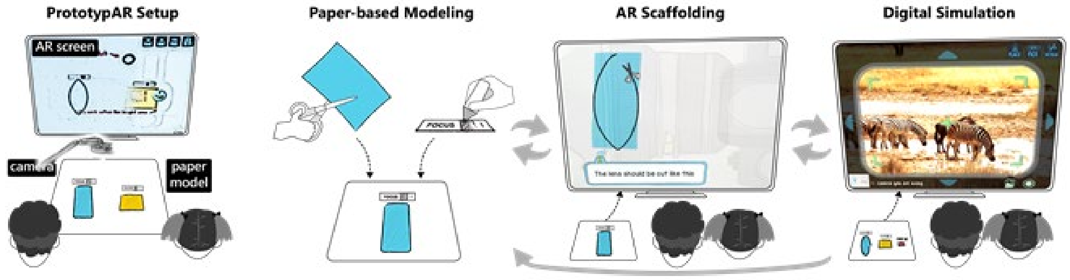


Figure 4-1: Using PrototypAR, an AR "smart desk" system, two children create paper-based models of a camera system that are displayed virtually on the screen. The children create a lens by cutting blue paper and filling a bar for the focal length, iterate on their models based on the AR scaffolding (in this case, to improve the shape of the lens), and experiment with their models in a digital simulation environment (e.g., taking a picture).

We built *PrototypAR*, an AR-based "*smart desk*" that allows children to prototype complex systems using familiar paper crafts, to learn about and correct mistakes via real-time AR-based feedback, and to test their creations in a digital simulation environment (Figure 4-1). PrototypAR's tangible modeling approach is intended to facilitate rapidly prototyping ideas [181] and to promote collaborative and playful experiences [241]. As a child builds a paper prototype, PrototypAR actively analyzes their work using computer vision to provide in-situ scaffolds via AR visualizations. The AR scaffolds provide design feedback [91,272] and bridge connections to existing knowledge to help children solve problems that otherwise might be too difficult [29]. At any point in the design process, the child can choose to test their model in a virtual simulation environment. Because the testing environment is digital, there is broad flexibility in how a design can be simulated and used for scientific inquiry (*e.g.,* testing hypotheses).

As initial work, our research questions are exploratory: What is the interplay between physical prototyping, AR feedback, and virtual simulations? What are the key benefits and challenges of a “smart desk” approach for learning? What aspects of PrototypAR seem to support design practices and complex systems learning? To begin addressing these questions, we designed and developed PrototypAR through three participatory design sessions with 10 children. The sessions enhanced our understanding of how children approach design and experimentation in a mixed-reality environment. We also gained design ideas for AR-mediated scaffolds, including increased support for iterative design and experimentation. Across the sessions, we developed three PrototypAR applications for exploring scientific phenomena and engineering concepts: *build-a-bike*, *build-a-camera*, and *build-an-aquarium*.

To evaluate PrototypAR, we conducted four single-session studies with 21 children who designed and test the *build-a-bike* and *build-a-camera* applications. Through a qualitative analysis of video recordings, questionnaires, and focus group interviews, we found that PrototypAR allowed children to progressively build complex systems models and explore a breadth of designs. Using the AR design feedback and simulations, children were able to repeatedly evaluate their prototypes and examine how different designs influence a system’s function. However, children struggled with designing experiments and interpreting results, which led to partial understanding or misconceptions.

4. 1 Participatory Design

To design PrototypAR, we used an iterative, human-centered design process that included participatory design activities with children and adult designers. Before describing our participatory design process, we first highlight four overarching design goals for PrototypAR, which were informed by prior work [122,220,287] and our own experience designing and evaluating children's learning tools.

- **Support engineering design.** We aim to support the engineering design concept and practice of generating, testing, and refining designs, which is foundational in STEM education [73,197].
- **Embed computer-mediated scaffolding.** Scaffolds should assess children's current understandings and adapt to their needs [184].
- **Facilitate inquiry.** To facilitate inquiry [39,72,217], we aim to automate the steps (*e.g.,* designing experiments and collecting results, and making interpretations).

Figure 4-2: The lo-fi prototypes emerged in the PD session. The ideas included (a) integrating testing function into the design environment (b) allowing for user control to the HELP design feedback and (c) enabling design of invisible attributes.

We co-designed PrototypAR using a participatory design method called *Cooperative Inquiry* [99]—design partnering in which adults and children work together to brainstorm, and test design ideas. Because the concept of PrototypAR is difficult to explain without a concrete representation, we used the technology immersion technique [118]. We had participants use an early prototype and elicit feedback and design ideas. In partnership with an on-going design group, we conducted three CI sessions with 10 children (ages 8-11) and six adult design partners. Our key questions included: (i) How do children approach paper-based modeling in an AR environment? (ii) What do children find difficult to use or understand with PrototypAR? (iii) What types of scaffolds do children need for modeling and experimentation?

4. 1. 1 Session 1: Children's Interaction with PrototypAR

To gain a preliminary understanding of how children interact with PrototypAR, we invited children to use an initial prototype of the *build-a-bike* application and share their ideas. After a brief introduction to PrototypAR (15-minutes), children and adult co-design partners spent 40 minutes using the system and offering their feedback in the form of "likes, dislikes, and design ideas" captured on post-it notes. A researcher synthesized high-level findings in situ and discussed them with the children and the adult partners.

Overall, we found that children were able to use PrototypAR to prototype models and conduct experiments. Based on observations and comments, children seemed to like the use of paper craft for modeling (e.g., "*making our own shapes*"), the responsive simulations (e.g., "*the gears mirror the paper size*"), and the personalized experiments (e.g., "*we can race our gears*"). After making prototypes, children tested them in the virtual simulation environment and observed how different designs affect the bike's performance. One group simulated three different prototypes and reported, "*The yellow [rear gear] is so small and it still won.*" Though children appreciated the usefulness of AR design feedback (*e.g.,* a child stated "*Yes it was helpful ...[to] tell you where to move it*"), some complained about the design feedback constraining their creative design (*e.g.,* "*It was picky*").

4. 1. 2 Session 2: Children's Design Ideas

In the second session, we asked children for ideas to improve the PrototypAR interface by building lo-fi prototypes. We used a *Bags-of-Stuff* [77] technique in which children use craft supplies (*e.g.,* fabrics, cardboard, markers) to communicate design ideas. Children presented their lo-fi prototypes and an adult partner synthesized the high-level themes therein. The following themes emerged (Figure 4-2): (i) highlight design errors early and at multiple stages of the design process; (ii) give users more control over design feedback (*e.g.,* when and at what level of detail); (iii) enable user control of "invisible" or abstract properties of a complex system (*e.g.*, exposure time for a camera shutter); (iv) enrich the prototyping experience with multimedia and multiple modalities (*e.g.,* speech interface, sound, 3D VR goggles).

4. 1. 3 Session 3: Challenges and Scaffolds for Learning

Finally, to identify what aspects children found difficult with complex modeling tasks and to elicit ideas for scaffolding, we conducted a session using the more complex *build-a-camera* application. Before the session, we incorporated design ideas from previous sessions into the PrototypAR, including: adding a hint button to allow child users to control how and when they receive feedback and additions to the prototyping interface to enable modification of component behaviors (*e.g.*, focal length of a lens). In this session, only one of the three groups succeeded in creating a complete prototype; the others were overwhelmed by the large number of design options involved in modeling the camera system. Because of their struggles, both children and adults suggested ideas to better scaffold learners, including: (i) focus users' work on one design element at a time; (ii) prompt users to switch between making and testing; (iii) suggest different options to encourage divergent design; (iv) assist users in setting up comparisons between prototypes in the simulation environment.

4. 2 System Design

PrototypAR operates in two modes: *AR design* mode and *experiment* mode. In the *AR design* mode, the user can prototype a complex system using lo-fi materials. PrototypAR actively tracks the work surface and offers adaptive *scaffolding* to suggest needed actions or provide corrective advice. At any time, the user can switch to *experiment mode* to make observations about *how* their prototypes function and *why* through virtual simulations.

PrototypAR is comprised of: (i) a *lo-fi prototyping interface* to support light creation of complex systems models; (ii) *AR scaffolds* to assist design tasks and learning; and (iii) a virtual simulation to enable experimentation with prototypes.

4. 2. 1 Lo-fi Prototyping Interface

The prototyping interface allows children to model complex systems using paper craft. To promote understanding through design, PrototypAR supports SBF modeling where the user models the structural elements and their behaviors that contribute to a complex system's overall function.

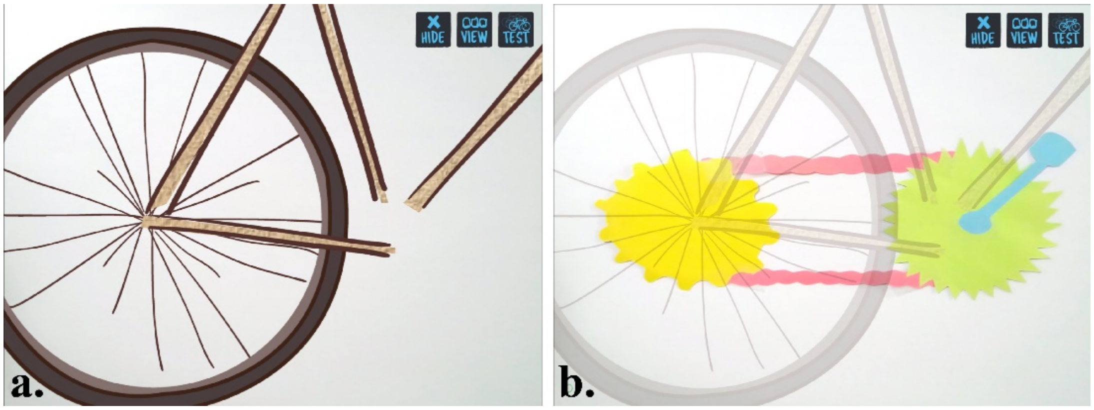


Figure 4-3: (a) The work surface is augmented with a design skeleton to help structural design; and (b) a final bicycle design with gears, pedals, and a chain.

Designing structure. In PrototypAR, the representation of *structural elements* includes an object's type, shape, size, position, and relationship to other elements. The user designs a structural element by selecting a colored paper, cutting it into a shape, and arranging it on the augmented canvas. When beginning a design, PrototypAR augments the work surface with a structural outline of the target system (Figure 4-3). For example, in the *build-a-bike* application, a bicycle sketch is shown with key structural elements missing like the gears, pedals, and chain. The outline—which is visible on the AR display—serves as a visuo-spatial cue to aid the child in thinking about the shape and size of each component (*e.g.,* the gear should fit within the wheel) and location (*e.g.,* the gear should be at the wheel's center). To help the child think about and distinguish different structural elements, we map the paper's color to a particular object type (*e.g.,* the back gear is yellow while the front gear is gear).

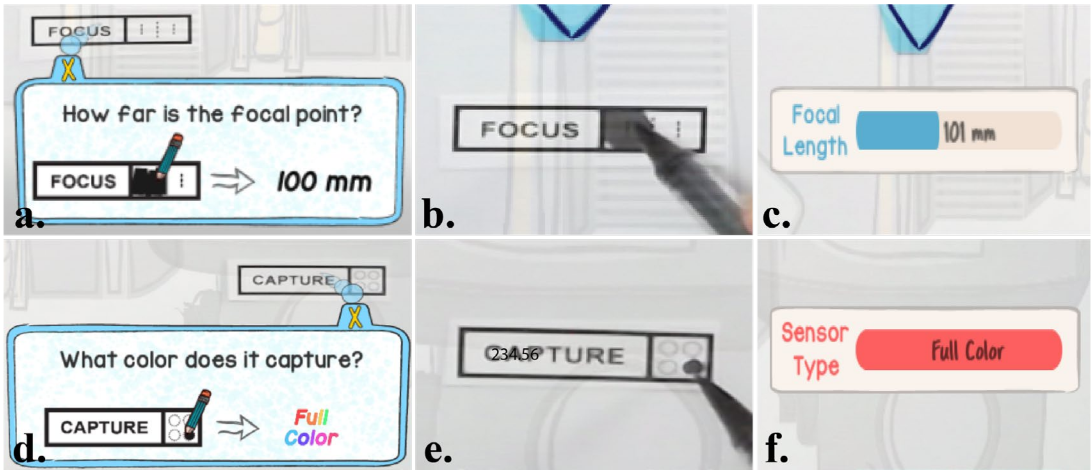


Figure 4-4: The behavioral labels are augmented with instructions to describe (a) a numerical value (*e.g.*, "how far is the focal point?") or (d) a categorical value (*e.g.*, "what color does it capture?"). (b, e) After the user fill in the label, (c, f) the system augments the label with a value.

Designing behavior. Because behaviors are more abstract and dynamic than structures, they are often more difficult to understand [113] and likely to be omitted in students' designs [115]. In PrototypAR, behaviors are designed explicitly via printed behavioral labels, which are placed next to their corresponding structure. Each label has a *behavior name* and a *data field*, which can be filled in with marker to specify a behavioral variable (Figure 4-4). There are two label types: *numerical* and *categorical.* Numerical fields are specified by filling in a horizontal progress bar while categories are selected by filling out a check box. To help the user learn about and specify behaviors, the AR system augments labels with definitions and instructions.

4. 2. 2 AR Scaffolds for Prototyping

PrototypAR provides three types of AR scaffolds, which were informed by prior research [40,216] and our participatory design sessions: (i) supportive scaffolds to provide domain knowledge related to system models; (ii) procedural scaffolds to guide learners through the PrototypAR interface; (iii) and strategic scaffolds to facilitate the design process.

Supportive scaffolds. To help resolve misunderstandings and aid progress towards design completion [122], supportive scaffolds give children immediate feedback and hints on potential design problems. The scaffolds are dynamically generated based on real-time recognition of the user's paper prototype and pop up next to the target of

Figure 4-5: Examples of supportive scaffolding feedback, suggesting: (a) a missing object, "you need a yellow gear here"; (b) a shape, "this object should be cut like this"; and (c) a position, "we need to move this to …"

interest using animation, images, and basic text. In total, PrototypAR provides six supportive scaffolds, including feedbacks for shape, position, and existence of an object. Three examples are shown in Figure 4-5.

Strategic scaffolds. To make design tasks more manageable for young children, PrototypAR provides two types of strategic scaffolds (Figure 4-6bc): first, PrototypAR highlights and limits the workspace to a particular area (*e.g., "let's work on this part*"). Craft materials outside of the highlighted work area are ignored. Second, PrototypAR helps facilitate new design ideas by suggesting new structure attributes (*e.g.,* gear size) or behaviors (*e.g.,* pedal speed). This scaffold is intended to let children focus on changing only one independent variable at a time to aid creating a set of prototypes useful for comparative experiments.

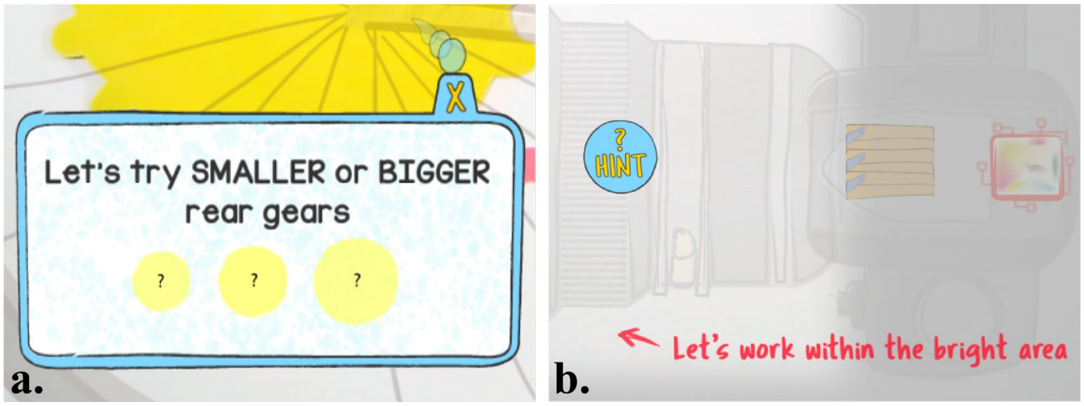
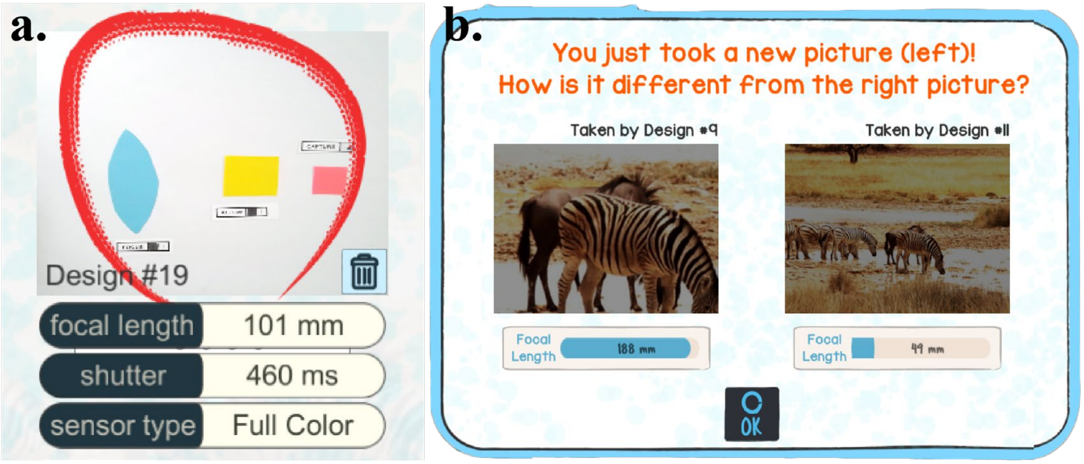


Figure 4-6: Examples of strategic scaffolds: (a) suggesting gears with different sizes; and (b) limiting the workspace to the area of the lens.

Procedural scaffolds. Procedural scaffolds help children use PrototypAR's prototyping interface as well as guide them through the iterative process of design and testing. For the first, the scaffolds remind children of paper colors for structure elements or illustrate how to design behavior labels (Figure 4-4) as needed. For the second, the system prompts testing a prototype when it is new, or asks for resuming design tasks after completing an experiment.

4. 2. 3 Virtual Simulations

At any point in the design process—from a partial prototype to a complete one—the user can test a digitized version of their work via *virtual simulations.* Simulations serve two purposes: first, to support the rapid testing of a design to enhance understanding and discover potential flaws; second, to provide an experimental testbed to directly compare and analyze performance across prototype designs.



focal length: 101 mm
shutter: 460 ms
sensor type: Full Color

You just took a new picture (left)!
How is it different from the right picture?

Focal Length: 188 mm
Focal Length: 49 mm

Figure 4-7: (a) The review panel shows a camera prototype along with its focal length, shutter speed, and sensor type. (b) The analysis panel shows the simulation results of two camera models that differ only by the focal length.

Towards these goals, we developed simulation support in both the AR design and the experiment modes. In the design mode, users can simulate individual components *in situ* via AR. This enables rapid testing of behavior, even at early stages of design. For example, the user can examine how the lens focus light rays at the focal point by watching an overlaid AR simulation. Users can then rapidly try different lens focal lengths in their workspace and observe the effect, which aids learning.

In the experiment mode, PrototypAR provides a simulation environment where users can test the function of multiple designs, make observations, and analyze results. While we custom built simulations for each application, our general approach is the same. Once the user enters the experiment mode, they are shown a *review panel* that displays images of their prototypes along with key design attributes (Figure 4-7a). The user can then select prototypes to test and begin the simulation. To facilitate controlled experimentation and reduce complexity, the review panel suggests clusters of prototypes that only differ in one design attribute (*e.g.,* rear gear size). After completing a simulation, an *analysis panel* organizes results by shared independent variables so the user can easily analyze and compare results (Figure 4-7b).

4. 3 Implementation

PrototypAR is comprised of four sub-systems: (i) the *object recognition and model building* sub-system builds digital models from the paper prototypes; (ii) the *model assessment* engine evaluates the state of the digitized model; (iii) the *design manager* provides guidance and feedback to the user in the AR design mode; and (iv) the *experiment manager* handles the simulation environment in the experiment mode.

4. 3. 1 Object Recognition and Model Building Sub-System

The object recognizer analyzes the user's craft workspace and attempts to classify paper elements as *structures or behaviors*. Because the user's hand can occlude the top-down camera and affect recognition results, PrototypAR's recognizer waits until there is no movement in the video stream for three seconds before executing the recognition pipeline (movement is calculated by examining differences in consecutive image frames [249]). The three second threshold was obtained from informal experiments and refined through the participatory studies.

Recall that each structure element is pre-assigned a unique paper color. To recognize structures, we cluster the *hue* and *saturation* channels of the image into *K+1* clusters, where *K* is equal to the total number of expected structures. We use *Gaussian Mixture Models* (GMMs) to train the K color models and cluster input pixels—a real-time method robust to camera noise [207,258]. To obtain shape information, we use the 8-way flood fill algorithm [109,202] with the pixels in each color cluster to find the image blobs. Finally, the recognizer examines the *connectivity* between classified structures by examining spatial distances between objects. In all, the recognizer generates computational models of structure elements that includes object type, contour shape, position on the canvas, and connectivity to other objects.

For the behavior labels, we developed a *behavior recognizer,* which uses character recognition to determine the label type and an *input variable recognizer* that uses two approaches for recognizing the numeric and categorical data. To recognize the label type, we use the *Tesseract OCR* [250]. To improve robustness, we apply Tesseract to multiple frames and select the result that best matches a pre-existing list of behavior strings using Levenshtein distance [163]. Once the label type is determined, PrototypAR examines the behavior variable. For numeric variables, PrototypAR uses blob detection to determine how much of the progress bar is filled in—the estimated fill portion is linearly mapped to a discrete value along a predefined range. For the categorical variables, PrototypAR divides the variable box into four quadrants and identifies the most saturated quadrant, which corresponds to a predefined behavior mode.

4. 3. 2 Model Assessment Engine

To assess the user's prototype, PrototypAR evaluates the constructed computational model. The *model assessment engine* works by comparing the model to a pre-built baseline model. For structure, we evaluate the *shape, position, connectivity,* and *missing or redundant* structure elements. While some assessment algorithms are trivial—for example, checking for the existence of a structure element in the user's prototype—others are more complex. For example, to evaluate shape, we compare contours between the user's model and a baseline model using geometric distance. To ensure a robust comparison, the baseline model is scaled and transformed to minimize distance. If the distance is larger than a predefined threshold (determined via participatory design sessions), the assessment algorithm generates an *incorrect* *structure shape* result. For behavior, we evaluate *missing* behaviors and *null* behavior variables, which require trivial comparisons with the baseline model.

4. 3. 3 Design Manager

The *design manager* uses the assessment results to provide real-time scaffolding feedback. When problems are found, the manager creates and visualizes supportive scaffolds. While *static scaffolds* render fixed visual content (*e.g.,* icons, text), *dynamic scaffolds* generate animations according to the user's model, often to show the user how to perform some action—for example, how to cut out a specific shape. To provide procedural scaffolds, the design manager monitors user interaction and records ongoing snapshots of a prototype and its corresponding digital model. For example, if a digital model looks sufficiently new and has not yet been tested, PrototypAR may suggest *testing* in the virtual simulation. For strategic scaffolds, the system dynamically dims and highlights part of the workspace to focus the user's attention. Finally, the design manager handles the *in situ* simulations of individual parts in the AR design mode.

4. 3. 4 Experiment Manager

The fourth and final sub-system, the *experiment manager*, controls the virtual simulations, including the *review panel,* the *simulation* environment itself, and the *analysis panel*. While the simulation environment and analysis panel need to be custom built for each application, the review panel provides a reusable architecture. Here, *PrototypAR* clusters similar prototypes together and helps organize experiments for prototypes that only differ in one *independent variable*. More specifically, given a pair of prototypes P_m and P_n, we calculate their *experimental distance D* as following:

$$\mathrm{D}(P_m, P_n) = \sum_{a_i \in A} d_{exp}(a_i, P_m, P_n)$$

$$d_{exp}(a, M, N) = \begin{cases} 1, & if\ design\ attribute\ a\ of\ M\ is\ diff\ from\ a\ of\ N \\ 0, & otherwise \end{cases}$$

Where A is a set of all design attributes. If $D(P_m, P_n) = 1$, we place both P_m and P_n in a cluster. The prototypes in a cluster can only differ by a single design attribute. After creating clusters through examining pairs, we merge clusters satisfying our conditions. Using this cluster information, the manager suggests a set of prototypes in the same cluster for experiment or comparative analysis.

4. 3. 5 4.3.5 Software Implementation

Rainbow is implemented using *Unity3D* for creating the AR environment, *OpenCVSharp* [298] for computer vision, and *Parallel Extensions* in *.NET FX* for data parallelism. For our studies, we used laptops with a Core™ i5-7300HQ processor and a GeForce® GTX 1050 graphics card. We logged performance during our studies: the average processing time for the *object recognition* and *model building* stage was 69ms, 350ms for *model assessment*, 399ms for the *design manager*, and 42ms for the *experiment manager*.

4. 3. 6 Demo Applications

To demonstrate and evaluate PrototypAR, we developed three example applications: *build-a-bike*, *build-a-camera*, and *build-an-aquarium*—each allows children to design, build, and experiment with different types of complex systems from mechanics to optics to ecology.

Build-a-bike Application

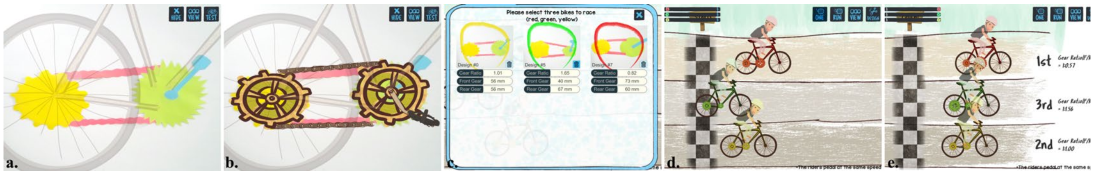


Figure 4-8: The build-a-bike application. (a) The user creates a paper model consisting of gears (yellow for the rear, green for the front), chains (red), and pedal (blue); (b) the AR simulation shows animated components; (c) user selects three prototypes for experiment; (d) the virtual experiment simulates a race with the selected bikes; and (e) the simulation result show the gear ratio of each bike to help analysis.

In the *build-a-bike* application, children learn about bike gearing systems by modeling front gears, rear gears, pedals, and chains. This application explores gear ratio and chain drive system concepts. To build a bike, children first craft two gears, connect them via chains, and place a pedal at the center of the front gear. For behaviors, AR visualizations show the causal process of the pedal rotating through the rear gear rotating. For virtual experiments, the system simulates performances of gear designs in a bicycle race—depending on the gear ratio, one turn of the pedal can make the rear wheel turn less or more than one full cycle. Children can race up to three of their designs simultaneously.

Build-a-Camera Application

In the *build-a-camera* application, children learn about camera optic systems by modeling lens, shutters, and sensors. This application emphasizes concepts of light

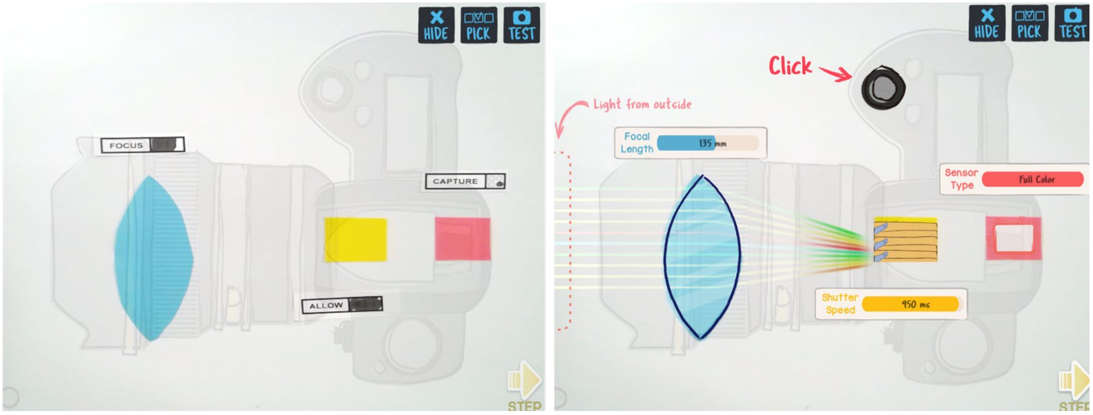


Figure 4-9: In *Build-a-Camera* application. (left) The model consists of lens (blue), shutter (yellow), and sensor (red). (right) The system visualizes the behaviors of individual components along with light rays.

focus and optical image sensing. To build a camera, children craft individual parts and then configure focal length, shutter speed, and sensor type via behavioral labels. AR visualizations show how light beams move through the parts and generate a picture (Figure 4-9). For virtual experiments, children can take pictures of various scenes using their camera designs—*e.g.*, a city at night, a rainbow, and a safari. For the dark city picture, for example, children's camera design with a fast shutter speed results in an almost black picture. Setting a slower shutter, children can see the city in a resulting picture, which allows them to learn the slower shutter speed makes a picture brighter.

Build-an-aquarium Application

In the build-an-aquarium application, children learn about aquatic ecology systems by modeling fish, sea plants, bacteria, and an air pump (inspired by [94]). This application emphasizes concepts of ecological balance and the nitrification process.

To build an aquarium, children craft and distribute individual models over the canvas. For behaviors, AR visualizations show the causal process of air-pumps supplying oxygen, fish consuming oxygen, bacteria converting ammonia to nitrate, and plants consuming nitrate. For virtual experiments, the system simulates production and consumption of the chemicals showing the current levels.

Figure 4-10: The *Build-an-aquarium* application is shown: (left) the paper-based model; and (right) AR visualizations of individual objects and the simulated levels of chemicals.

4. 4 Evaluation

To examine how children interact with and use PrototypAR and to uncover opportunities and challenges for learning, we conducted four single-session evaluations with 21 children (ages 6-11; *M*=8.5; *SD*=1.6) at two local facilities. Based on our findings from the participatory design sessions, we recruited participants for each session based on age: (i) 10 younger children (ages 6-9) used the *build-a-bike* application in two sessions; and (ii) 11 older children (ages 9-11) used *build-a-*

camera in the other two sessions. We leave the *build-an-aquarium* application for future work.

All sessions followed the same general procedure but differed in length for administrative reasons: two sessions lasted 60 minutes and the others lasted 90 minutes. Sessions began with a pre-activity questionnaire (5 minutes). Children were introduced to PrototypAR (5 or 10 minutes) and then used the system for 35 or 50 minutes. Finally, sessions concluded with a focus-group interview and post-activity questionnaire (15 or 25 minutes). Children worked in groups of two except one child who worked alone (*i.e.,* 11 groups total). Each group had an adult facilitator who helped with PrototypAR and led the interviews.

After the introduction, children were given two tasks: first, to build at least one paper-based prototype that functioned properly in the simulator; and second, to complete a design challenge such as designing bike gears with certain performance or a camera to take pictures with a specified quality. The facilitators, if necessary, provided domain knowledge (*e.g.,* the meaning of gear ratio), prompted reflective discussions (*e.g.,* "*What do you think about the result?*"), and helped with resolving difficulties (*e.g., reading scaffolding texts for children*).

4.4.1 Data and Analysis

We collected pre- and post-activity questionnaires, photos and videos, focus group interviews, facilitator field notes, and system logs including interaction events and, crucially, prototype images—the latter enabled us to examine what each prototype looked like and how they changed over time. The questionnaires examined users' general experience with respect to engagement and usability using child-friendly Likert scale questions (based on [102]). The focus group interviews asked open-ended questions to understand modeling and experiment experiences, children's learning, utility of the scaffolds, and design preferences.

To analyze the video data, we followed a peer-debriefing process [34,165]. We first formulated an initial coding scheme, which included the themes of engineering design process, how children interact with AR scaffolds, learning through construction and experimentation, and the role of peer support [215]. *Researcher A* coded a sample group's data and met with two researchers who were in the sessions to review the initial results and update the codebook by resolving disagreements, clarifying details, and generating new codes. *Researcher A* then coded another random group's data and met with another researcher to review the results. After repeating this with another sample group's data, Researcher A coded the rest of the data. Finally, researchers synthesized findings including related quantitative data (*e.g.*, how many times children tested their models).

4.4.2 Findings

We describe patterns of design and iteration, interaction with system scaffolds, learning opportunities and challenges, collaboration, and engagement. For the Likert-scale questions, a rating of '5' indicates 'best.'

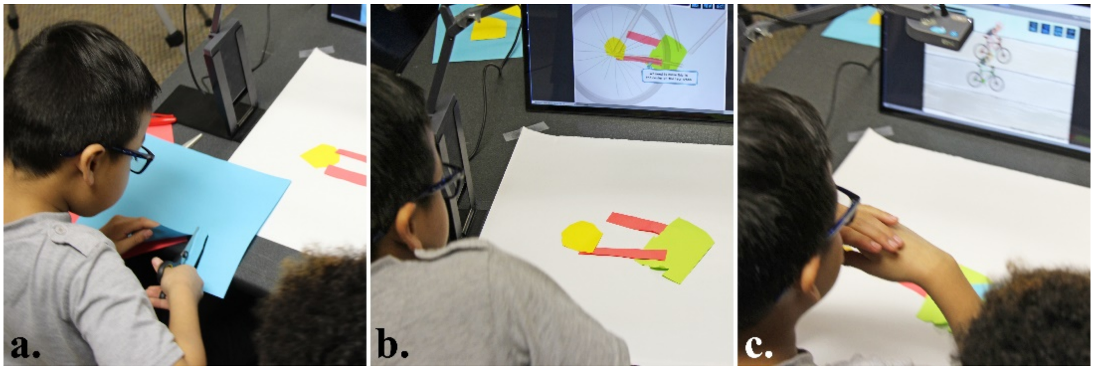


Figure 4-11: Children engaged in iterative process of (a) making paper models, (b) evaluating the model through AR visualizations, and (c) experimenting with prototypes in the virtual simulation.

Design and iteration

We analyzed how children designed and evaluated prototypes with PrototypAR. System logs revealed that children approached design largely in two stages—first, a *bottom-up* step to build a complete model and then an *exploration* step to examine various forms of the complex system (Figure 4-11). We observed that, in early design stages, children focused on adding missing entities (*e.g.*, adding a chain), moving parts into the right places (*e.g.*, placing a gear at the center of the wheel), and refining shapes (*e.g.*, cutting a rectangular lens into an elliptical shape). Groups progressively built parts until they had an initial model with properly sized, shaped, and placed components.

Once children built a complete design, they shifted their attention to explore a breadth of designs. Children replaced design entities (*e.g.*, replacing a front gear with a larger one or increasing a shutter speed) iteratively, often reusing existing paper pieces to quickly replicate a previous design. The system logs showed that groups created 7.8 distinct prototypes on average. The distinct prototypes exhibited different simulation results in the virtual experiment, which clarified how individual components function (*e.g.*, two camera models with fast or slow shutter speeds resulted in dark and bright pictures respectively). On the post-activity questionnaire, "*I could see differences between prototypes in the virtual simulation*", all children except two selected '4' or '5' (*M*=4.6; *SD*=0.6). We also observed that children enjoyed building "extreme" designs, and this helped them explore and understand the design space. For example, in the *build-a-bike* application, 3 of 5 groups created both giant and tiny gears. One child stated, "*It's going to be funny! It's going to be funny!*" making a giant gear.

In both stages of design, we noted that the AR visualization and in-situ experiment feedback prompted children to try new design ideas. First, children identified design issues by observing how changes in individual components affected the simulation. For example, a child realized the gears in his prototype were not rotating due to missing chains; he said, "We need to connect two gears...otherwise it wouldn't move." This example demonstrates how PrototypAR's just-in-time feedback prompted children to realize that their system was missing a component (i.e., chains) and was therefore incomplete. In addition, the interactive simulation results prompted children to reflect on their prototype designs as a whole. For example, in the *build-a-bike* experiment, one child suggested increasing a front gear after watching a bike with a larger rear gear lose a race saying, "*I think the front [gear] has to be big. [rear* *gear] has to be small*". Similarly, in the *build-a-camera* experiment, one child suggested changing a shutter speed after seeing a dark picture taken by a camera prototype saying, *"let's try a full [shutter speed]"* On the post-activity questionnaire "*I think the Test (virtual experiment) was helpful*", children appreciated the usefulness of the virtual experiment; 15 of 21 selected '4' or '5' (*M*=4.0; *SD*=1.2). In the interview, a child affirmed it stating, *"It helped a lot, if [there was] no test button, we couldn't know how good the camera is."*

Interactions with scaffolds

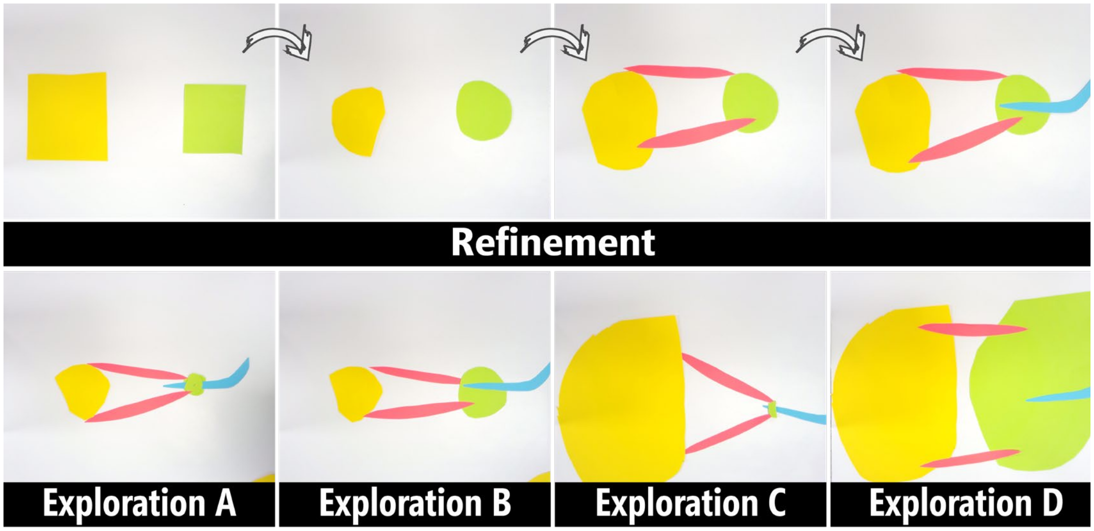


Figure 4-12: A group progressively built a complete bike model (above). Then, they created divergent prototypes for their experiments (below)

Children used and reacted to the three scaffold types differently. For supportive scaffolds, which provided design feedback, children used them to evaluate individual models but used them less often as they gained experience. In early design phases, we observed that children made use of supportive scaffolds almost whenever one was available. They chose to open a *Hint*, read the feedback dialog, watched animations of design suggestions, and discussed the ideas therein. When asked if the scaffold was helpful on the post-activity questionnaire, 18 of 21 participants selected ‘4’ or ‘5’ (*M*=4.5; *SD*=0.8). A child stated, “*It helped you make the bike.*” However, we found from video data that children did not fully follow the design suggestions; rather, they used their own ideas or interests for designs. For example, two groups created and tested rectangular gears while the scaffold suggested a circular shape. In the later phases of design, children became less likely to use *Hint* scaffolds. From the system logs, we found that 76% of Hint usage, on average (*SD*=14%), occurred in the first half of the design process.

In terms of strategic scaffolding, the scaffold that illuminated and constrained the current work area (*e.g.,* highlighting the area around the lens in the *build-a-camera* application) seemed to help children *divide and conquer* the complexity of a design. For example, from the system logs, we found that all groups successively created at least three different designs for a specific part when the workspace was limited. After iterating on a part, children repeatedly switched the workspace to the other part until they had a full-fledge prototype. In contrast, children did not always seem to follow the strategic scaffold that actively prompted them to explore specific design attributes (*e.g.,* a dialog suggests increasing or decreasing a front gear size). From system logs, we found that children had already started modifying these attributes before receiving the suggestion or simply did not follow PrototypAR suggestions even after reading them.

Collaboration

We analyzed how the tangible approach supported communicating ideas [261], sharing control [296], and concurrent interaction [80]. Though children were not assigned specific roles during the activity, from the video data, we observed a set of collaborative behaviors including splitting design tasks, discussing design ideas*,* and sharing observations. For example, Emma and Noah were working together on designing a shutter. Noah read design feedback about the shape and clarified it talking to Emma , "*Just make it like a small square. It doesn't have to be like same size*". Later, Emma wondered about the level of the shutter speed, asking "*Should we make it full?*" Noah nodded saying, "*Full!full!*" Finally, in the virtual experiment, Noah compared two pictures taken by different camera models and explained how the focal lengths influenced them stating, *"this is zoomed-in and this is zoomed-out."*

However, we also observed that children had difficulties managing conflicts in their design ideas and manipulating a shared virtual interface. For example, when Ava and Liam were making a bike prototype, Liam suddenly cut an existing front pedal without discussion, and Ava got annoyed shouting, "*What are you doing*!?" In another example, Ethan and Jacob were selecting bike prototypes to simulate. When Ethan was selecting prototypes, Jacob suddenly stopped Ethan saying "*I will do this,*" complaining, "*You did last time, can I do it this time?*" These conflicts led to unpleasant experiences, which were resolved by a facilitator.

Content learning

We examined how using PrototypAR contributed to children's understanding of complex systems. These results should be considered preliminary given the small sample size. During the activity and the group interview, 10 of 11 groups reported that they learned about what objects exist in a complex system and how they behave. For example, a child whose group succeeded in creating a complete camera model after 11 iterations stated, "*We learned three different parts of camera*" The other child in the same group added, "*we learned how to make it [the lens] focus …learned [the] shutter allows light to pass or not*" Another child—who tested different focal lengths and observed the resulting phenomena in the AR visualizations—reported that he learned how a lens manages light stating, "*Lens makes the light focus at one place*"

While all the groups reported their findings about how system components influence the system's function, we found that their understanding could be incorrect or partial. From verbal observations they made while tinkering with the simulations and in their responses to the interview question "*what did you learn?*", children shared accurate conceptions of how individual parts contribute to a system's function including: "*Bigger rear gear does not make the bike faster*" and "*If we don't put the shutter, it's (picture) just all bright*". We found that two of 5 groups who used *build-a-bike* demonstrated misunderstandings such as "*If green [front] and yellow [rear] gears are small, it makes the bike slower.*" and 4 of 6 groups who used build-a-camera ended up with partial understandings about the system—*e.g.,* a group could not grasp how the shutter works but demonstrated understandings about the lens and the sensor. We return to these misconceptions in the Discussion.

Experimentation challenges

Related to the above, we observed two primary challenges children had in conducting experiments with PrototypAR: designing experiments and analyzing observations. To understand the relationships between design attributes and a system's function, it is critical to design and conduct comparative experiments—testing a set of prototypes that have different attributes for a single independent variable. Though PrototypAR automatically suggests a selection of appropriate prototypes to compare, we found that children often selected designs that looked most different or even, seemingly, at random. This made it difficult for children to make accurate claims from reviewing the experiment results. For example, in the *build-a-bike* application, a group ran experiments with a *big* prototype having two big gears and prototypes having gears of different sizes, and concluded with the misconception, "*If gears are same size, the bike goes faster.*"

We also observed that children had difficulties analyzing the simulation results. Even in cases with well-designed experiments, children often could not explain why they got the results or drew inaccurate conclusions. For example, a group tested a camera with a fast shutter speed to take a picture of a dark scene that actually requires a slow shutter speed. When the simulation resulted in black photos, they could not reason why this happened and became disengaged after several tries. A child in the group commented in the later interview, *"(it was) difficult to be color (as) you wanted."* The group even thought it was a system malfunction, asking a facilitator to fix the problem.

Engagement

The majority of participants reported having fun with PrototypAR; 16 of 21 children responded '4' or '5' (*M*=3.8; *SD*=1.6) to the post-activity question, *"I had fun using PrototypAR"*. In group interviews, children liked using craft materials (*e.g., "Using different materials and colors"*), making a creative or extreme design (*e.g.,* a *"huge gear"*), AR visualizations (*e.g., "Cool effect on white paper"*), and virtual simulation for testing (*e.g., "To see what pictures would look like"*). However, four participants had a negative experience. One participant commented that the visual differences between real objects and virtual objects made it less interesting: *"we got to have this gigantic, but we have this tiny one [in a virtual one]"*. We also found that repeatedly making the same system (*e.g., "Making a lot of bikes"*) and constraining design (*e.g., "It wasn't so exciting, I had to follow lots of rules"*) made the process seem tedious.

4. 5 Discussion

Learner-centered approach. With PrototypAR, we envisioned a learner-centered environment [103] where children can address their unique interests and deepen understanding. Specifically, we posited that children can learn about different aspects of complex systems by constructing the *structure* of a system model, observing AR simulations of component *behaviors*, and comparing the *functions* of their different designs in the virtual experiment. Indeed, the groups were able to learn different aspects of a complex system from the same activity. For example, in the *build-a-camera* application, one group reported learning about how the focal length affects the zoom-level of a picture while another learned about the shutter affects the brightness of a picture. Children enjoyed having this level of control in their design and experimentation process (*e.g.,* chose to iterate on a specific part based on their interest rather than from suggestions by strategic scaffolds). This tendency resulted in positive outcomes such as engagement with design iterations and unexpected findings (*e.g.*, a child was surprised to see bigger chains did not affect the bike speed). But, it also limits opportunities to examine all the parts of a complex system and develop understanding about how the system works as a whole, which often led to partial understandings. Future work should consider scaffolds that can support iterative expansion of children's component-level focus while highlighting comprehensive interrelationships and functions of these components.

Tinkering vs. structured scaffolding. Constructionist learning environments that support playful exploration can afford children serendipitous opportunities for "ah-ha" moments, yield options for experimental comparison [36], are more aligned to authentic science inquiry as practiced by professionals [52], and may promote intellectual risk taking, a key for science learning [13]. Likewise, our findings suggest that free-form prototyping promoted children's engagement and encouraged personal, interest-driven experimentation. However, their prototypes did not always lead to systems-level understanding or accurate mental models. Their enjoyment with testing the extreme bounds of a design ("huge gears!") hinted at a nascent awareness of design constraints, but lacked a systematic approach, such as controlling for variables. Moreover, the children's eagerness to create silly, random designs often precluded them from taking up the system's scaffolded suggestions, which led to misconceptions. These findings affirm the need to balance learners' free-form play with structured guidance for inquiry [55]. Future designs should consider how scaffolds can respond and adapt to children's own ideas, in minimalist but directed ways that guide their efforts to design and execute systematic modes of inquiry. Because children often ignore or feel constrained by lock-step scaffolds that limit their design freedom, future work should also consider interactive design features that prompt learners to reflect upon their ideas and modify them iteratively rather than randomly.

Tangible interface. Our findings suggest that PrototypAR's tangible prototyping interface lowers entry barriers to modeling complex systems and helps children understand visual and spatial aspects of complex systems. However, our current system does not yet support more complex models that may involve layered, occluding structures, large numbers of interacting components, or ways to represent abstract processes [115,125]. To address these limitations, future work should explore hybrid approaches of combining physical and virtual interfaces, extending the current 2D design space to 3D, and adding auxiliary input modalities (*e.g.,* voice or embodied interaction).

AR design environment. While prior work has explored AR modeling systems for adults or high school students [142,227], our work demonstrates the benefits of AR for elementary-level children to access domain knowledge via supportive scaffolds, deal with design complexity in guidance of strategic scaffolds, and draw design ideas from reflections on AR visualization of models. However, our current AR approach limits immersion. The user interface is distributed across the physical desk and the screen, which can negatively impact usability. For example, we observed that some children tried to select virtual menus on the screen by tapping the canvas. Future work should explore other AR techniques (*e.g.,* projection display) to better integrate the physical and virtual.

4. 6 Summary

We built PrototypAR, an AR system to support complex systems learning through iterative craft modeling, AR-based scaffolding, and virtual experiments. We studied two PrototypAR applications using a single-session study design. While this is appropriate for our exploratory goal of studying user interaction, investigating opportunities and challenges, and drawing design implications, the study is insufficient for examining learning or long-term engagement. Our findings show that a mixed reality approach—accompanied with scaffolding—can allow children to engage with modeling and experimentation of complex systems. This suggests that complex systems learning is approachable for young children given appropriate learner-centered tools and environments, extending Danish *at el.*'s findings [63].

In summary, our contributions include: (i) a novel AR-based prototyping system for children that supports paper-based modeling and simulation of complex systems; (ii) findings from participatory design studies and user studies that illustrate how children can engage in iterative modeling and personalized experiments as well as identify opportunities and challenges; and (iii) reflections on a tangible modeling approach for children's complex systems learning.

Chapter 5: ARMath- Mathematizing Everyday Objects

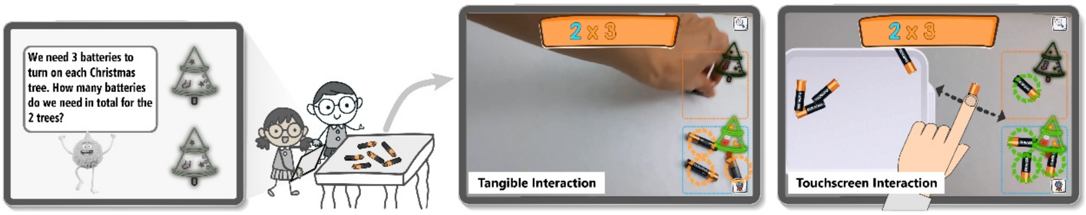


Figure 5-1: ARMath, a mobile AR system, recognizes everyday objects and enacts a life-relevant situation where children can discover and solve math problems. A virtual agent presents a story, such as needing batteries to turn on animated Christmas trees. Children interactively perform the multiplication problem, 2 (trees) * 3 (batteries), either by directly manipulating physical batteries or moving virtual batteries on the touchscreen.

Tangible manipulatives such as blocks and puzzles have long been used in elementary mathematics to promote exploration and understanding of abstract concepts [200,239]. Recent research suggests that using familiar, life-relevant objects engages children in applying math skills and promotes the math relevance [169,182]. With advances in computer vision (CV) and augmented reality (AR), we now have an opportunity to explore how to link traditional math learning to everyday experiences. While emerging research in AR-based math learning has focused on immersive visualizations for 3D geometry exploration [142], non-symbolic number training [18], and virtual tutors [208], we explore the integration of everyday objects, virtual storytelling, and AR-based scaffolds.

We built *ARMath*, a mobile AR system for children (K-3) that recognizes everyday objects, turns the objects into math manipulatives, and presents a virtual situation in which children can solve a math problem. ARMath is comprised of four components: (i) a *perception engine* that recognizes objects and their mathematical attributes, (ii) a *problem generator* that presents stories, word problems, and formulas tailored to the objects, (iii) an *interaction engine* that supports interaction with physical or virtual objects for problem solving, and (iv) a *scaffolding engine* that provides audio-visual guidance, procedural feedback, and virtual math tools. With ARMath, children can explore both the mathematical composition of everyday objects—for example, the angles of a book or a picture frame with an AR protractor—as well as use the manipulatives to interactively solve arithmetic problems such as counting physical coins to purchase a virtual ice cream.

As initial work, our research questions are exploratory: What are the opportunities of using everyday objects for math learning with AR? What aspects of ARMath seem to engage children in the mathematization experience? What are the design implications for AR-based math learning tools? Our research is inspired and informed by prior AR learning systems that demonstrate the potential of turning familiar environments into personally meaningful and engaging learning spaces [150,220,263,287]. We extend the research in three ways. First, to promote relevance of learning, our approach leverages objects existing in everyday life beyond specialized tangible objects [61,227] or locations [50,135]. Second, we target young children (grades K-3) who are less likely to see connections between their daily life and mathematical concepts. [200,244]. Lastly, to inform the design of user interaction, we compare tangible and virtual manipulatives that co-exist in AR.

To create ARMath, we employed an iterative and human-centered design process involving four participatory design sessions (two with teachers, two with children). In the teacher-based sessions we co-designed ARMath-based learning activities and critiqued existing AR learning tools. In addition, we conducted design sessions with children using an initial ARMath prototype that integrated the teachers' ideas. These sessions examined early user interfaces, solicited feedback, and cultivated new design ideas, which were integrated into a final ARMath system.

To evaluate ARMath, we conducted five single-session user studies at a local children's museum: 27 children participated (ages 5-8). In our analyses of video recordings, pre- and post-activity questionnaires, and focus groups, we found that children were physically and cognitively engaged with ARMath, actively used scaffolding features, and felt that they had learned mathematical concepts. Interestingly, our findings also highlight how failures in AI can be used as learning opportunities, transforming the child from learner to teacher. However, children struggled with cognitive gaps between physical and AR worlds, certain AR-assisted interactions (*e.g.,* physically manipulating objects while also viewing the AR tablet screen), and a shortage in conceptual scaffolds.

5. 1 Participatory Design

To design ARMath, we employed a participatory design process [242] involving teachers, children, and adult designers. Informed by prior work [153,238] and past experience in designing AR learning tools, we set out to explore five overarching design goals for ARMath.

- **In situ visualization of mathematical concepts.** To promote conceptual understanding, ARMath should visualize abstract concepts in objects—e.g., the circular shape of a clock.
- **Use of everyday objects.** We aim to support using everyday objects as math manipulatives and as a means for enacting a specific everyday situation.
- **Contextual math problem.** To promote relevance of learning, math word problems should be contextualized as part of real-life practices.
- **Tangible and virtual interactions.** For problem solving, we aim to offer two interaction options: manipulating physical objects or virtual objects on the touchscreen.
- **Learning goals.** ARMath-based math content and interactions should be aligned with formal elementary mathematics curriculum [200].

5. 1. 1 Participatory Design (PD) with STEM Teachers

To design ARMath and its learning activities, we conducted a participatory design (PD) session with 17 STEM teachers. We collected session video, teacher-created artifacts (*e.g.,* design mockups), and session summaries written by the research team. For analysis, we used thematic coding [34] and peer-debrief [255]. Two researchers coded the entire data corpus, followed by peer-debriefing with two other researchers to ensure validity.

Teachers critiqued ARMath mockups and co-designed new features and learning activities. To scaffold the session, teachers were provided with handouts of math topics for each grade level [200] and ideas cards for facilitating brainstorming. During the critique, teachers were positive about ARMath's potential to turn everyday objects into math manipulatives and promote relevance of learning—e.g., *"ARMath gives opportunity for children to apply mathematics models and see them in action."* A teacher appreciated the potential for learning with large numbers, stating, *"children can practice large numbers without having to get additional materials."* However, teachers shared concerns about technical glitches such as lagging or incorrect object recognition (*e.g., "what if the system says 3 for 4 apples?"*).

In teachers' designs, we identified three emergent themes: (i) providing alternative visualizations; (ii) scaffolding arithmetic operations, and (iii) supporting interactive analysis of shapes. For example, teachers suggested displaying equations for an on-going situation or highlighting geometric primitives (*e.g*., vertices, angles). For arithmetic, they included graphical scaffolds for strategies (*e.g.,* visualizing *equal-number groups* for multiplication) and a monitoring tool that records children's approaches (*e.g., "success or failures on problems, progress tracking")* and reports them back to teachers or parents. For geometry, teachers emphasized inquiry into a real shape (*e.g.,* asking the number of corners in a *STOP* sign), interactive construction (*e.g.,* dragging a book to create a 3D cube), and vocabulary learning.

5. 1. 2 Participatory Design with Children

Following our PD sessions with teachers, we developed an initial prototype, and conducted two *Cooperative Inquiry (CI)* studies [69] with 8 children (ages 8-12) and 5 adult design partners. In each session, groups of 2 or 3 children and an adult partner worked together to test an initial ARMath prototype and create designs.

In the first session, we employed a *technology immersion* [118] technique to understand the new approach and brainstorm design ideas. During the test, children recorded their "likes", "dislikes", and "design ideas." Adult partners then synthesized high-level themes and discussed them with all the groups. In the next session, we used the *Bags-of-Stuff* [77] technique in which children use craft supplies (*e.g.,* fabrics, cardboard, markers) to build lo-fi prototypes of their design ideas. After the two sessions, adult partners and researchers synthesized key features from the children's design ideas, which resulted in the following implications.

Extending context in objects. While children liked using everyday objects, more relevant contexts are needed to promote motivation. Children seemed to be engaged with manipulating everyday objects, noting *"like using everyday objects" "would like to use ARMath at home if I can use different kinds of objects."* However, some got bored quickly because there was no context related to *"why we need to count or add coins."* Children and adult partners suggested presenting virtual situations that involve math operations—*e.g.,* add coins to a bank to buy a toy car.

Repairing AI errors. Because the CV technique for detecting objects and user manipulations sometimes fails, adult partners and researchers agreed on the need for integrating human intervention to identify and correct errors. While children appreciated the AI (*e.g., "like the system know the colors of objects and types of objects"*), they also noticed that the AI can be wrong or slow. A child stated, the *"camera get confused or can't keep up with me moving objects."* These errors often led to generating erroneous math problems or rejecting the correct answers.

Mobile AR environment. We observed cognitive and behavioral issues related to the mobile AR environment: (i) confusion about a limited view in AR, (ii) less attention on virtual representation, and (iii) distraction by everyday objects. Because the AR camera produces a perspective different from children's eyes, children were confused by gaps between the real world and AR view. For example, when children placed four coins on the table, the camera captured only three and showed incorrect feedback.

5. 2 5.2 System Design: Perception, Problem Generation, Interaction, and Scaffold

Informed by our PD sessions, we developed the final ARMath system—a mobile AR app—with five application modules for counting, addition, multiplication, division, and geometry. To use ARMath, children find objects needed in a virtual situation, putting them in front of the AR camera. Then, children can solve a math problem by using the physical objects or the touchscreen. In the meantime, children can move around with the device to explore objects or sit at a table to interact with objects found.

ARMath consists of four parts: (i) a *perception engine* that uses CV to recognizes everyday objects, (ii) a *problem generator* that creates storytelling, a math word problem, and a corresponding equation based on the perception, (iii) an *interaction engine* that detects interaction with physical and virtual objects for problem solving and (iv) a *scaffolding engine* that visualizes abstract concepts and helps with math procedures.

5. 2. 1 Perception engine

To recognize everyday objects and their mathematical attributes, the *perception engine* uses CV and machine learning (ML) including *object detection and tracking* to recognize objects in real-time and *semantic understanding* to draw math information. At any time, children can use the *repairing UI* to correct detection errors.

Object detection and tracking. The first step in the perception process is *object detection* that recognizes all the objects in the camera image, determines the class (*e.g.,* coins, bottles), and estimates the segmented images [119]. We use state-of-the-art object detectors—combining deep learning-based *SSD* [171] and *Mask RCNN* [108]—that are robust against scale, perspective, and light. To maintain consistent detection over time, *multiple object tracker* connects the object instances between video frames, using a common method of iterative prediction and association [20]. To gain robustness against mobility and user action, our tracker suspends the process when movement is detected in gyroscope data or the video stream.

Semantic understanding. To draw mathematical information such as set, count, or length, semantic understanding performs *grouping*, *geometry analysis*, and *math inference*. Grouping is a common strategy for whole number concept and arithmetic operations [35,172]. For grouping, the system detects spatial and color clusters of objects by applying the k-means clustering [106] and GMM classification [207]. For geometry analysis, the system applies contour line analysis [262] and extracts key components such as vertices and sides. The *math inference* analyzes mathematical attributes of an object using planar tracking [95] and CNN-based regression [221]. For example, it estimates the height of a painting or the water level in a bottle—this is excluded in the modules for low accuracy.

Repairing UI. The system involves children in the perception process, allowing for correcting object detection results or geometry shapes. The repairing UI augments objects with visual indicators of *detected-by-camera,* and allows children to correct false-positive or false-negative cases by simply tapping them on the screen. Similarly, to rectify errors in geometry analysis, the system offers an optional interface to draw the shape on top of an object (Figure 5-5d). The system simplifies the hand-drawn shape toward a primitive shape (*e.g.,* straightens a squiggly line).

5. 2. 2 Problem generator

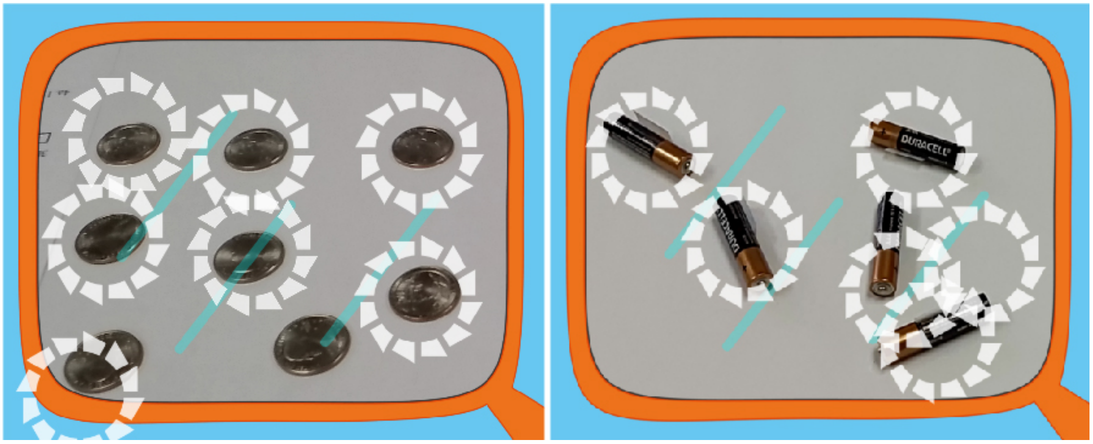


Figure 5-2: The repairing UI; white circles are overlaid on recognized objects. Children can fix (left) false-negative or (right) false-positive errors by tapping them on the screen.

The problem generator adapts pre-existing graphics and dialogs for storytelling, math word problems, and equations to the current setting of physical objects. All the dialogs are presented both via text and text-to-speech (TTS).

Storytelling. The storytelling engine populates virtual objects, avatars, and dialogs that engage children in a virtual math situation. While storytelling uses static models and animations of virtual objects and avatars, it adapts dialogs to the physical objects involved. The dialogs are implemented as a sequence of speech bubbles that children can interact with to proceed.

Math word problems. During the storytelling, the system generates a math word problem. The system adapts a pre-existing problem template to the objects and their math attributes (*e.g.,* count, shapes), and generates a question. For example, in division module (Figure 5-2), when 8 chocolates are found and a random divisor 2 is selected, the avatar asks, *"We need to distribute the 8 chocolates equality into the two gift boxes. Then, how many chocolates do we have in each box?"* To capture the key information in the problem, an animation highlights both objects in time synchronization with the TTS output.

Equations. In addition to the word problem, the system translates the mathematical situation and presents it abstractly in an equation—*e.g.,* "8 ÷ 2 = ?" This exposes children to symbolic representations, allowing for learning about what equations are composed of and connecting the on-going math operation with the abstract symbol [260].

5. 2. 3 Interaction engine

ARMath provides two interaction modes for interactive problem solving including: *tangible* mode and *touchscreen* mode (Figure 5-3). In the tangible mode, to perform arithmetic operations, children can place, move, or remove physical objects on the tabletop surface. In the touchscreen mode, for the same operations, children can drag-and-drop multiple virtual objects on the touchscreen. In both modes, the system continuously tracks the user manipulations and translates them into math operations.

Tangible interaction. To support tangible interaction, the system examines the status of individual objects within the AR world and detects the status change. The system examines physical objects' spatial relationships with virtual objects by comparing their positions and areas—*e.g.,* testing if a chocolate is contained in a virtual box. Then, the status result is compared with the previous frames to detect change; the change is regarded as a user manipulation (*e.g.,* adding a chocolate to the box). When a manipulation is detected, the system combines the status results of all objects, translates them into a mathematical representation, and evaluates the representation for providing feedback.

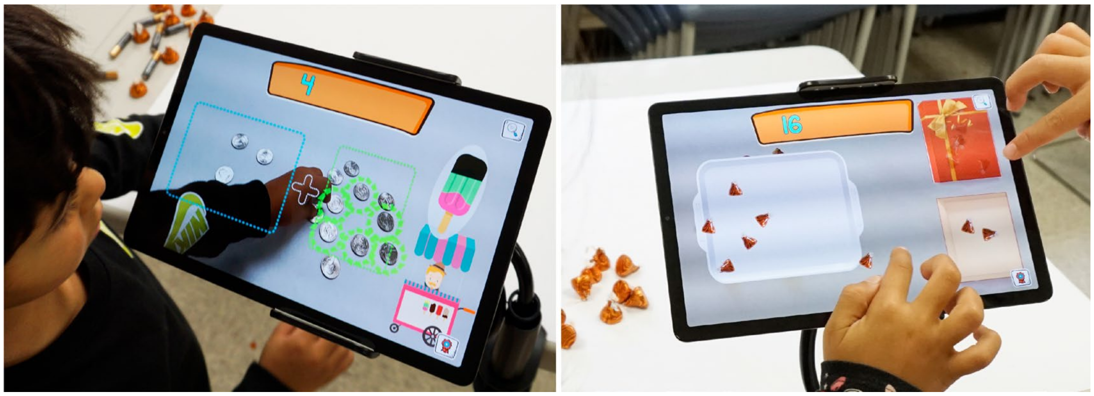


Figure 5-3: (a) In tangible mode, children use physical coins on the table for addition. (b) In virtual mode, children drag-and-drop virtual chocolates on the touchscreen for division.

Virtual interaction. To support virtual interaction, the system performs the same process for the tangible interaction, but it considers virtual manipulatives instead. At the beginning, the system creates virtual manipulatives for the existing physical objects. To maintain connection between physical objects and virtual manipulatives, the virtual objects use real-image textures, present on top of the physical objects, and play realistic sounds upon drag-and-drop actions. Moreover, the system duplicates the virtual objects and provides extra manipulatives so that children can operate with large numbers as needed.

5. 2. 4 Scaffolding Engine

Informed by our PD studies and prior work on scaffolding strategies in learning technology [133,229], ARMath embeds scaffolds including: (i) contextual scaffolds to aid situating math problems in everyday life contexts; (ii) conceptual scaffolds to help understand math concepts; and (iii) procedural scaffolds to guide actions for problem solving.

Contextual Scaffold. The AR imagery, virtual storytelling and the math word problems allow children to think about computations and concepts applicable to a specific life situation. In addition, for children who are more familiar with symbolic equations than story problems [167], the symbolic equations for arithmetic problem are presented.

Conceptual Scaffold. To help children understand math ideas, ARMath augments real objects with graphical representations of abstract concepts such as numbers, sets and geometry primitives. The graphic is dynamically generated for the manipulatives. For example, in the addition module (Figure 5-4), the system augments two groups of objects with red and green rectangles respectively so that children can perceive the summation of two distinct sets. As another example (Figure 5-5f), a rectangle object is augmented with graphics of its vertices, sides, and angles.

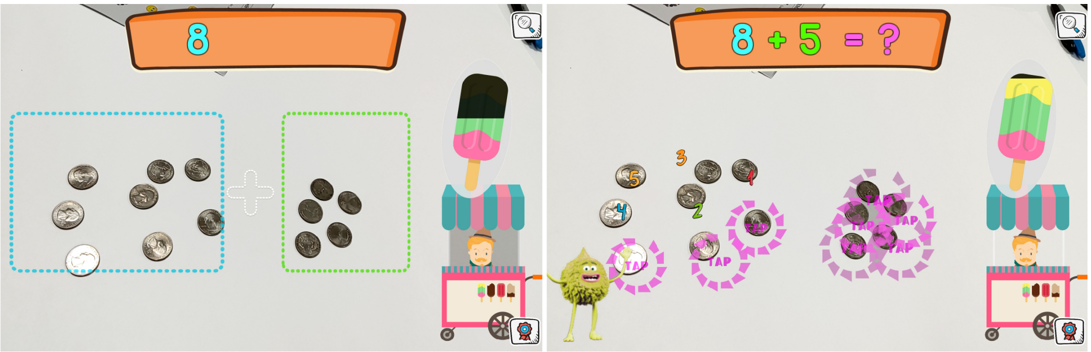


Figure 5-4: In the addition module, (left) after adding 5 coins (green box) to 8 coins (blue box), children count the total by using the interactive counters (purple circles).

Procedural Scaffold. The procedural scaffolds include feedback for user manipulations and virtual tools for numerical counting and measurement. For feedback, the system continuously translates the current status into a mathematical form, and generates feedback based on the evaluation of the form. For example, when children add 2 coins to 5 coin for *“5 + 4 = ?”*, the system prompts, *“add 2 more ”* For virtual tools, at the end of arithmetic modules, the system augments (physical or virtual) manipulatives with *interactive counters* that help children count numbers. As children touch a counter, it displays the total count of objects. In the geometry module, children can use a virtual protractor. When children rotate a protractor arm to measure a corner angle, the systems shows the angle value (*e.g., “70°”*) and reads its name (e.g., *“acute angle”*).

5. 2. 5 Software Implementation

ARMath is implemented using *TensorFlow* [1] and *OpenCVSharp* [298] for the perception process and *Unity3D/Android* [269] for AR framework. While not limited to a specific device, the application is tested and deployed with Galaxy Tab S5e devices.

5. 3 Application Modules

Each module offers a four step user experience: (i) engage in a virtual and mathematical situation; (ii) find specific everyday objects; (iii) interactively solve a math problem; and (iv) review and solve a formal symbolic problem (Figure 5-5). To begin, Victor (a friendly virtual ‘monster’ agent) illustrates a situation that requires math and asks children to find specific everyday objects (*e.g.,* 10 batteries or 8 chocolate candies). Once children place the objects in the AR finder (Figure 5-2), Victor asks the children to confirm if the objects are recognized correctly and fix any potential errors. Victor then presents a math word problem (*e.g.,* dividing 8 chocolates into 2 groups) and guides children in manipulating the items—either by tangibly moving objects under the AR finder or virtually on the touchscreen. After finishing the operation, children review their work as Victor summarizes the result with numbers, words, and visual cues. Children then solve a formal symbolic problem (*e.g.,* $8 \div 2 = ?$) to ensure they understand the concept before receiving an animated icon as a reward. If children repeat the arithmetic modules, the problems become harder, involving larger numbers. Below, we summarize the five math modules—see the supplementary video for a demonstration.

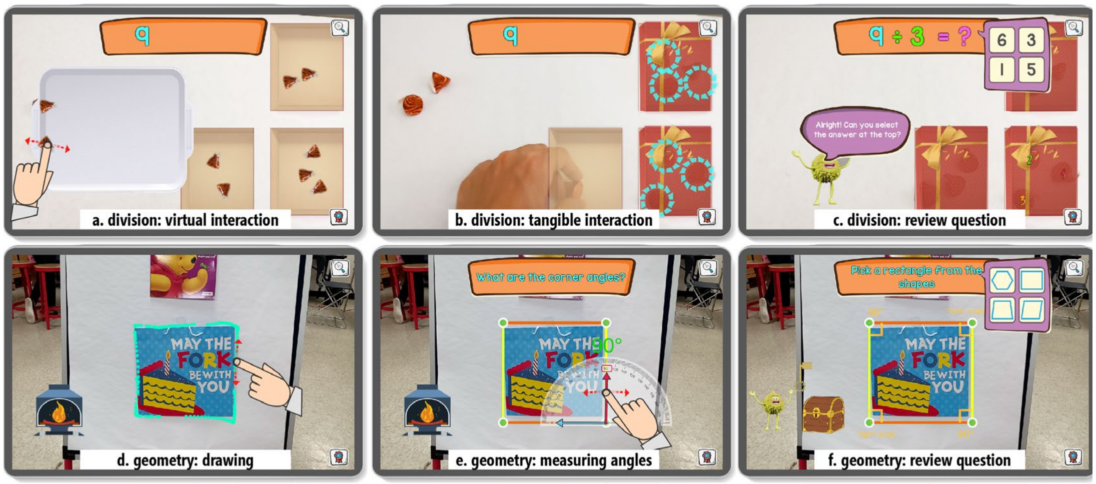
Counting. As an introductory module, children practice recognizing the number of objects in a group by counting. Victor asks children to find objects and presents a *"how many"* situation. After finding some objects, children count the number of objects by moving (physical or virtual) objects into a virtual tray; the tray displays the on-going count. When all the objects are moved, Victor asks about the number of objects in the tray, highlighting the objects with purple circles—*interactive counters*. The counters enumerate numbers as children tap them.

Addition. Children develop understandings of addition and its connection to counting by counting two sets of objects [194]. Victor asks children to find coins for an ice cream and presents an *"adding to"* situation. A blue rectangle, indicating a set, is overlaid on the objects initially found, and children add a certain number of (physical or virtual) coins to a green rectangle (Figure 5-4). When finished, Victor asks about the number of coins in the two rectangles, highlighting them with interactive counters.

Multiplication. Children understand the meaning of multiplication by representing objects in equal-size groups [194]. Victors asks children to find batteries for Christmas trees and presents a "*successive addition*" situation. Children place a certain number of (physical or virtual) batteries in a box for each tree. When finished, Victor asks about the number of batteries used for all of the trees, highlighting them with interactive counters.

Division. Children understand the meaning of division by distributing the whole number of objects [194]. Victor asks children to find chocolates for gift boxes and presents an "equal sharing" situation. Children place the same number of (physical or virtual) chocolates in each virtual gift box. When finished, Victor asks about the number of chocolates in each box, highlighting them with interactive counters.

Geometry. Children understand geometric components of a rectangle by describing them in an object [194]. Victor asks children to find a rectangular object and presents an *"investigation"* situation of making a rectangle. Using an image of the object found, children draw a rectangle, identify vertices and sides, and measure corner angles with a virtual protractor. When finished, Victor highlights the components and asks children to identify a rectangle out of four different shapes.



a. division: virtual interaction
b. division: tangible interaction
c. division: review question
d. geometry: drawing
e. geometry: measuring angles
f. geometry: review question

Figure 5-5: In division, after finding 9 chocolates, children divide them equally for three gift boxes. They divide either (a) virtual or (b) the physical chocolates. In the end, (c) children count the number of chocolates in a box (right-bottom) and complete the equation. In geometry, after finding a rectangular bag, children (d) draw the rectangle, identify vertices and sides, and (e) measure corner angles. After reviewing the shape, (f) children identify a rectangle out of four shapes.

5. 4 Evaluation

To understand how children could use ARMath and to uncover opportunities and challenges therein, we conducted a field deployment at a local children's museum. Participants were recruited through the museum. We held five identical sessions; 27 children participated (ages 5-8; 14 girls). Children were grouped in age-based pairs though seven children worked alone—for a total of 17 groups. In each session, there were up to four groups of children participants and three adult facilitators. Facilitators helped children use ARMath, provided math knowledge as needed, and conducted a post-play focus group. For one group, a parent stayed with the children for a personal reason.

Each session lasted 80 minutes including an introduction to ARMath and a pre-activity questionnaire (15 min), using ARMath with tangible and virtual interactions (45 min), and a post-activity questionnaire and focus group (20 min). Sessions were conducted at a room with tables. Each table was equipped with a tablet stand. Each group was assigned a table and an ARMath device. Children were allowed to select a math module and move around the room to find and bring everyday objects to the table. Everyday objects recognized by ARMath (*e.g.,* batteries) were provided

5. 4. 1 Data and Analysis

We collected questionnaires, session videos, focus group interview recordings, field notes, and system logs. The pre-activity questionnaire examined children's math learning experience (*e.g.,* engagement, use of materials) using child-friendly Likert scales [102] and posed problems designed to elicit their math knowledge. The post-activity questionnaire and focus group included questions about user experience (*e.g.,* fun factors, interaction), self-assessments of learning, and failures in AI. The system logs recorded achievement, interaction, and screenshots.

To analyze the qualitative data, we employed a thematic analysis [34], combined with peer-debriefing [165], where data was iteratively examined and reviewed to identify themes and patterns. Two researchers developed an initial codebook through independent, open coding of data from two different groups. The researchers then worked together in a round of axial coding to clarify, merge, and resolve individual codes, which was followed by a second round of independent coding with the emerging codebook; and another collaborative discussion to resolve disagreements, further clarify details, and finalize the codebook. Finally, two researchers split the field study data to synthesize and triangulate findings across all data sources.

5. 4. 2 Findings

We present findings related to user engagement, scaffolds, interaction modes, experiences with failures in AI, learning potential, and challenges. For Likert questions (scale: 1-5, 5 is best), we report means (*M*) and standard deviations (*SD*).

Figure 5-6: With the geometry module, a group explored three different rectangular objects in the surrounding environment.

Engagement

The "engagement" theme emerged from our observations of children using ARMath and what attributes supported their engagement. On the post-activity questionnaire, most children indicated having fun with ARMath; 19 out of 27 children gave 4 or 5 (*M*=4.1; *SD*=1.3) to the question *"Using ARMath is fun."* In the follow-up interview, children liked using everyday objects (*e.g., "It was really fun because I'm using real objects"*), life-relevant actions (*e.g., "I liked division because I like dividing things"*), and visualizations (*e.g., "I liked the numbers on the screen"*). However, four children shared negative reactions; three of whom were on the younger end of our age range: 5-6 years old. For example, one child (age 5) commented, "I *don't like shapes because I don't understand it*." Further work is needed to identify what additional scaffolds might help younger learners understand solve these more complex problems.

We observed that several children were cognitively engaged to reinforce concepts by repeating modules. Children often repeated the same module back to back, trying new objects or challenging themselves with a harder problem (*e.g.,* more objects to count or divide). For example, a group did the geometry three times in a row, collecting a variety of rectangular objects (*e.g.*, painting, worksheet, and envelope; Figure 5-6). In another group, after finishing a multiplication module, a child was excited to tackle a harder problem, saying, *"Hey, we can do it again, we can do it more, I guess it goes harder."*

Our video analysis revealed that our storytelling approach to presenting math problems engaged children emotionally. They expressed surprise, responded quickly to system prompts, and were motivated to perform math tasks. Most children appeared immersed in the virtual situation and worked hard to help Victor address his math problems. For example, when Victor asks for more coins to buy ice cream, all the children were quick to add some coins. Having successfully completed an addition module, many children chose to repeat their accomplishment, expressing surprise that Victor would then demand a larger number of coins: *"Oh my God! Eleven! We need eleven coins! Really?,"* Another child emphasized the narrative context for the multiplication module, stating *"I liked multiplication because I needed to take batteries to turn on the trees."*

Scaffolds

We examined how children used the scaffolds present in ARMath and what scaffolds facilitators supplied *in-situ*. Our video analysis showed that children used *interactive counters* to help them find solutions and that equations triggered conversations about formal symbolic math. For example, when the formula "2 x 4 = ?" is introduced, one group initially answered "6." After realizing this was incorrect, one child used the interactive counter to count along, "*one, two, three…eight!*" before correctly selecting "8." Others used the counter to verify their answers, while two groups that had correctly calculated their answers from equations also seemed to check their solutions by slowly counting the objects aloud.

Our video analysis indicated that ARMath's approach of showing virtual representations alongside concrete physical representations, overlaid by symbolic notation (e.g., "÷" operator) prompted math discourse and supported children's sense-making efforts. For example, when the equation "6 ÷ 2 = ?" was shown, an older brother made the connections for his sister via the interface, pointing out, "*Do you* *know what 6 divided by 2 is? … So 6 divided by 2 is three because putting three two times equals six.*" Similarly, another child asked about the multiplication operator, "*What is this X?*" after completing two rounds of the multiplication module; a facilitator explained.

The interactive protractor seemed to be the most engaging feature of the geometry module. We observed that 11 out of 17 groups played with the protractor needle to explore different angles, often reading aloud with the ARMath verbal scaffold. For example, after trying 5 different angles with the protractor, one child observed, "*When it goes over this (90 degree), it is hmm Obtuse angle!" "This is acute. Is it because it is less than the right angle?"*

We observed that facilitators offered three types of scaffolds: (i) providing domain knowledge (*e.g.,* geometry vocabulary); (ii) explaining AI limitations with metaphors (*e.g., "The computer's brain is tired", "It cannot see stacked coins"*), and (iii) directing children's attention to the virtual agent (e.g., *"What does the puffy guy say?"*)

Tangible and Virtual interactions

Our results show little difference in preference or children's natural approach. In the post-activity questionnaire, children showed equally high preference for the two interaction modes; they gave a mean rating of 4.2 (*SD*=1.3) for the tangible and 4.4 (*SD*=1.1) for the virtual. One child noted that virtual manipulation afforded the same interaction as the tangible one, "*I liked moving (virtual) objects on the screen because we can move them anywhere like on the table.*" Also, we did not observed tendency in children's natural approaches. Because our participants had little experience with tablets or AR, we assumed that children preferred physical manipulation over virtual. However, we did not see significant differences between or within groups.

We observed notable differences in the pace of arithmetical operations and collaboration. In our video analysis, children took a rapid and single-step approach in tangible mode, whilst they took a slow and multi-steps approach in virtual mode. For example, when prompted to move a group of 4 batteries, a child quickly placed a handful of 7 batteries and promptly adjusted upon the system's feedback (*e.g.,* "*too many").* Conversely, despite the ability to move multiple virtual objects concurrently, the child carefully moved batteries one by one, counting aloud until he got the right number. Interestingly, collaborative operations occurred more frequently in virtual mode. For example, one group split division tasks, saying "*Now you take two on that, and now I take two on the other.*" Then, they took turns dragging-and-dropping the virtual chocolate in the boxes. In the later tangible division, only one child distributed chocolates quickly but in a less organized way.

Failures in AI

We analyzed how children understood and reacted to image recognition errors and their thoughts about the "imperfect" AI. While most children experienced several occurrences of recognition errors, they also seemed to understand ARMath's AI constraints. Children then helped the system recognize objects by placing objects more appropriately and waited patiently rather than expressing frustration. For example, once facilitators explained ways to help Victor (the virtual agent), most children tried to spread objects so that the system could distinguish adjacent objects. Children even gave Victor up to 20 seconds to recognize objects—*e.g.,* a group screamed with joy after waiting 5 seconds. However, one group that was not explicitly told the AI "sometimes makes mistakes seeing" struggled to manipulate objects (*e.g.,* moving the tablet vs. object; holding an object too close to the camera). With the repairing UI, most children quickly fixed the false-negative detection errors, but they showed negative reactions to false-positive ones. At the beginning, children were told *"you can help Victor because he does not see very well."* During the study, they immediately fixed unrecognized objects and seemed happy with that—e.g., *"Hey look, now he sees it."* Surprisingly, few children ignored the errors. However, when Victor indicates false existence of objects, children expressed negative reactions, thinking Victor was lying (*e.g.,* a child complained, *"he circled (recognized) when it was not there").*

In the focus group, we asked what children thought of helping correct Victor's errors. While two groups shared negative experiences (*e.g., "He was wrong often. I found it annoying when I had to help him"*), eight groups liked to help (*e.g., "Everyone makes mistakes and learns from the mistakes. People like helping"*). Moreover, three groups indicated that they learned from repairing errors. One child said, "*He was a little confused about the math. I think I helped him and I learned some when I helped him.*"

Learning Potential

Our exploratory evaluation consisted of a single 80 minute session with each group, so achieving or measuring learning outcomes was not a primary goal. However, our analysis indicates ways that ARMath could contribute to learning. In the post-activity questionnaire, 22 of 25 children agreed *"ARMath helped learn math"* (*M*=4.2; *SD*=1.0). Specifically, children indicated that ARMath reinforced arithmetic operations (*e.g., "I think I learned a bit more about division*") and symbolic notation (*e.g., "I learned numbers", "The symbol. I forgot the name of the symbol"*). With ARMath, children wanted to learn more operations (*e.g., "minus, not just plus"*), measurement (e.g., *"length and width"*), and other shapes (*e.g., "Hexagon"*).

Figure 5-7: (Left) a child struggled with adjusting physical interaction to the AR view. (Right) two children split tasks between physical and virtual surfaces.

Our video analysis highlighted a potential to promote children's motivation and confidence. Children's comfort and familiarity with everyday objects motivated play with larger numbers or different shapes. For example, one child explored double-digit addition because she *"just wanted to have a lot of coins."* ARMath also seemed to encourage children's confidence by allowing them to solve otherwise difficult math problems on their own. As one child explained, *“ARMath makes me learn better. I struggled with division at home. I learned about division.”* Another child boasted, *“This is my second problem. Dad see, look, I did these two (counting and addition).”*

Challenges

We observed three primary challenges: (i) issues with hand-eye coordination [37,220]; (ii) discrepancies between children’s conception of a shape and how it looked in AR view; and (3) insufficient conceptual scaffolds. We observed that most children experienced difficulties with hand-eye coordination, as the mobile AR environment makes coordinating physical movements through an AR screen more difficult. In particular, children struggled to place physical objects at the right place on-screen. In response, some children devised a collaborative solution: in three groups, children split tasks so one child manipulated physical objects while the other monitored the AR screen. One child directed, “*I will keep an eye on the screen, I will tell you what batteries you move*" (Figure 7).

The geometry module’s system logs showed that children struggled with perspective distortion. The AI performs geometry analysis best when an object is as close to a true rectangle shape as possible. Consequently, both system and facilitator prompt children to take pictures in this way. However, children often ignored the instructions or failed to notice the AI made a distortion error (Figure 6 right). Children paid little attention to the object’s on-screen presentation; rather, they stuck to their conception that the physical object was a rectangle, despite the AI errors.

5. 5 *Discussion*

AR-interactive storytelling. Our findings revealed an opportunity for AR storytelling to engage children in mathematization. These findings extend the benefits of AR storytelling—previously limited to literacy education [22], edutainment [132], and journalism [203]— to math learning. ARMath's interactive story enabled children to actively participate in meaningful math tasks using everyday objects in familiar contexts. This affirms Billinghurst *et al.*'s design requirement that "*interaction beyond navigation*" is essential for compelling AR experiences [25].

Bridging concrete and abstract math. Our findings demonstrate an opportunity of AR visualization to bridge the gap between hands-on math activities and formal symbolic math. Translating mathematical situations into abstract representations is critical in elementary school mathematics [44]. To our knowledge, however, little research has shown how hands-on learning with manipulatives helps children make conceptual connections between abstract and symbolic representations [183]. Our findings suggests that showing abstract equations in AR can trigger children's interest or reinforce explicit connections between the symbolic and concrete—*e.g.,* children questioned the symbols or explained the equations to peers.

Opportunistic use of everyday objects. Prior work in AR UIs explored how everyday objects enrich haptic experience [111] or controller interfaces [110]; however, little work has focused on how they can be used for learning. We have only begun to explore the opportunity of everyday objects as manipulatives for children's math learning. Our findings affirm Liu *et al.'s* suggestion that using real-world manipulatives can be generally helpful for learning [169], as well as Mbogho *et al.*'s claim indicating that students can be engaged with actual physical objects [182]. Our work extends this knowledge by showing how everyday objects can be engaging manipulatives and prompt playful, story-based mathematizing in familiar, meaningful contexts.

Child-AI Interaction. Child-AI interaction can be characterized by a high probability of failures (*e.g.,* conversation breakdowns with Alexa [17]) and children's conception of machines as "like a person" [174]. Our work extends the knowledge by examining children's reactions, attitudes, and efforts to repair system errors in learning contexts. We found that, with facilitators' help, children could understand AI behaviors and adapted their manipulations to system recognition limitations. These findings support Beneteau *et al*.'s claim that youth can understand machine learning (ML) behaviors [17], with adult mediation, as suggested by Cheng *et al* [48,288]. At times children still reacted negatively to the AI's deceptive behavior of the false-positive errors (*e.g.,* similar to *creepy* deception [288]), which suggests the need for precision and recall [212] in CV and ML techniques.

Furthermore, our findings regarding children's efforts to repair AI errors suggest a new opportunity for learning. Our observations of children's persistent engagement affirm Cheng *et al.*'s [48] finding that repairing mechanism is essential for children's persistent use of conversational AI and extend it to vision-based learning applications. In our study, when children took steps to repair AI errors, they had an opportunity to evaluate the AI's mathematical misunderstandings and learn by correcting them. As a result, two children explicitly mentioned 'correcting Victor' as an avenue for learning (*e.g., "I learned some when I helped him")*. Future work may explore designs or learning activities that can leverage this child-AI interaction and study potential cognitive processes involved.

Virtual vs. Tangible manipulatives. Our work contributes to research attempting to compare children's use of tangible and virtual manipulatives in math education [32,178,192]. Unlike prior work, however, our AR approach afforded the opportunities to compare the two modalities in the same mixed-reality environment. While children showed little difference in their preferences, our findings indicate that the touchscreen interaction promotes collaboration and reflection by slowing down children's actions. We attribute these results to the touchscreen's physical constraints (in terms of space and action), giving credence to Manches *et al.*'s [178] claim that manipulative characteristics of interfaces can influence children's numerical strategies. Our work extends this knowledge by demonstrating how slower-paced, space-constrained virtual interfaces can encourage collaborative math learning.

Limitations and future work. While our work demonstrates the potential of AR and everyday objects to promote mathematization, our study has limitations related to usability, the repairing UI, and parent/teacher facilitation. Our mobile AR approach highlighted issues related to hand-eye coordination, discrepancies between children's perception and AR view, and stabilizing the device, which may limit practical use cases. More immersive devices such as *HoloLens* or *AR glasses* may address these limitations. In addition, more effective repairing schemes need to be designed to integrate AI capabilities in learning tools. Lastly, future work may explore when and how to involve parents or teachers in children's mathematization efforts.

1. 1 Summary

We built ARMath to support mathematization experiences in everyday life. Leveraging CV and AR, ARMath recognizes physical objects, enacts a mathematical situation, and supports interactive problem solving or geometry analysis. Through participatory design with teachers and children, we elicited design ideas useful for ARMath as well as general AR-based STEM tools. Our user study allowed us to understand how children engage with everyday objects for learning, their interaction patterns in tangible and virtual surfaces, and uncovered new opportunities of child-AI interaction for learning. While ARMath demonstrates the potential of AR for everyday math, more work is needed to address usability issues, design effective child-AI interaction, and enhance learning.

In summary, our contributions include: first, introducing a real-time mobile AR system for mathematizing everyday experiences; second, enumerating design implications through participatory design studies with teachers and children; and lastly, reporting evaluation results and reflections about the opportunistic use of everyday objects for math learning, tangible *vs.* virtual interactions, and learning with imperfect AI technology.

Chapter 6: Conclusion

The overarching goals of the dissertation is design, develop, and evaluate AR learning systems that can engage children (ages 5-11) in STEM experiences and explore user interaction techniques that use personal data, artifacts, and objects. To attain these goals, we conducted the three threads of research including ShardPhys, PrototypAR, and ARMath. The design processes and exploratory evaluations allowed us to understand the opportunities and challenges of AR for children's STEM learning and demonstrated AR-supported learning systems and user interaction techniques. Below, we summarize the major contributions and discuss directions for future work.

6. 1 Research Contributions

This section synthesizes the formative contributions related to how AR could support children's STEM learning and opportunities and challenges therein. We also summarize system contributions of each AR system focusing on its key features.

6. 1. 1 Formative Contributions

A goal of this dissertation is to understand the design space of AR-based learning technology. To that end, we conducted participatory studies with teachers and children. Specifically, teachers examined the affordances of AR learning tools, discussed potential issues and design requirements, and designed AR-based learning activities aligned with standard curriculums. We also invited children to understand how children use our systems and gather design ideas through co-design sessions. In the later part of research, we field deployed each system to evaluate how it affords STEM learning and draw design implications. Across the three systems, these efforts generated empirical knowledge about how AR can support or challenge children's STEM learning and what needs to be considered in use or design of AR-learning tools.

6. 1. 1. 1 The Potential of AR for STEM Learning

Our research explored and demonstrated how AR systems can afford three types of STEM learning including collaborative inquiry, complex systems learning, and mathematization. We identify key features and affordances of AR for children's STEM learning, highlighting benefits of promoting engagement and scaffolding.

Scientific Inquiry. AR can engage children in scientific inquiry by enabling observation and analysis of data in-situ. While playfully interacting with a virtual content, children can inspect its scientific phenomena via visualizations of data or simulation to answer a scientific question. In SharedPhy, teachers designed an inquiry activity where a group of children perform an assigned physical activity (e.g., jumping jacks, standing, and running) and examine similarities and differences of their breathing rates. As their bodies are augmented with live physiological data, children can simultaneously collect and analyze the data to develop explanations for their questions. Indeed, our evaluation shows that children engaged in open-ended inquiry [243] through posing their own questions, testing hypotheses using visualizations, and drawing conclusions based on the data. This allows children to enhance their understanding about the scientific content as well as familiarize themselves with the inquiry practices.

Engineering Design-based Learning. By enabling rapid prototyping and simulation of ideas, AR can engage children in constructing, and testing solutions to engineering problems. This aspect of affordances relates to the tangible modeling approach in PrototypAR. Our work builds on prior work attempting to integrate an engineering design-based approach with science instruction [19] by demonstrating the feasibility of AR. The AR approach is effective because children can create extreme, silly, or even random designs without potential risks or cost in the physical world. The lightweight and unencumbered design of artifacts can facilitate children's exploration of scientific concepts, yielding options for experimental comparison [36]. Likewise, our evaluation suggests that free-form prototyping can engage children in the iterative process of design and testing, enabling personal, interest-driven experimentation.

Mathematization. Augmenting physical environments (*e.g.,* a scene of physical objects) with their mathematical attributes and contextual problems can engage children in the process of mathematization [277]. With advanced computer vision, the mobile-AR system can support the everyday math practice—recognizing and applying mathematical ideas in everyday life—enhanced by computer-mediated scaffolds and storytelling. To that end, ARMath is designed to support instructional approaches for mathematization such as posing a math word problem based on a realistic contexts, exploring math concepts through unstructured manipulation of objects, and hands-on activity for math discovery. This approach engaged children both cognitively—repeating the same math problem or trying new objects—to reinforce mathematical concepts as well as emotionally to motivate and emotionally to promote children’s motivation and confidence.

6. 1. 1. 2 Challenges of AR-based Learning

The participatory design studies and the evaluation of the three systems allowed us to understand what aspects of AR may hamper children’s learning experience and challenges in our approaches. We synthesize key challenges and discuss implications for addressing the issues.

Interaction with Computer-mediated Scaffolding. We envisioned providing scaffolds via AR visualization, however, the computer-based scaffolds sometimes failed to capture children’s attention or assist them in completing tasks. In PrototypAR, some children ignored the dialog-based scaffolds that were strategically designed to prompt exploring a specific design attribute, which led to a missed opportunity for learning about the attribute. ARMath also provides children with domain knowledge (e.g., math vocabulary) and instructions for arithmetic operations; however, children often paid little attention to them. The way scaffolding is provided, children’s engagement with interactive features, or the degree of intervention may have contributed to the challenges. Further work to improve the scaffolding approach in AR environment and integrate teachers’ or parents’ scaffolds is needed to effectively achieve learning goals.

Reflection and Discussion. A challenge when designing AR-based learning activities is to balance immersion in interactive tasks such—e.g. crafting and tangible manipulation— with moments of reflection and discussion for learning. In our co-design sessions, teachers raised concerns about supporting reflection of learning through the interactive tools. Though our studies were designed to encourage children to reason their hypotheses or thoughts, some children did not voluntarily participate in discussion with peers nor reflect on their observations. In SharedPhys, vigorous physical interaction sometime limited opportunities for reflection as players physically interacting with the visualizations were less focused on learning concepts as reports. Without reflection on their activity, children were likely to develop misconceptions with visualizations or experimental results. Future work may explore incorporating structured approaches to help children slow down and reflect on their interactive learning.

Interacting with Physical and Virtual Worlds. The co-existence of physical and virtual objects can confuse children about interaction and visual conception. For example, in PrototypAR, children tried to interact with virtual menus on the screen by tapping the physical canvas. In ARMath, Children experienced difficulties in coordinating hands and eyes as the mobile AR makes physical movements through an AR screen harder. Children were also confused by gaps between what is shown on the AR screen and the real world, which was due to AR camera's perspective difference from children's eyes. In these cases, children preferred their physical-world conception paying little attention to what is shown on the AR screen. More immersive devices such as HoloLens or AR glasses may address these challenges integrating the physical and virtual view but may introduce their own challenges, such as user comfort and communication with peers.

Logistical Issues. Major concerns emerging from our studies with educators were related to availability of AR devices, teachers' or parents' experience with AR, and lesson management. Especially for the collaborative learning in SharedPhys, it should be critical to allow everyone to wear a sensor so that children are equally involved on the learning task. Despite the latest advances in the field of AR, the questionnaire and interview data indicate that teachers have little experience with AR technology or AR-based learning. To practice AR learning in the formal learning environment, the following should be addressed including: scaffolding for instructors to understand what they can do with the technology or cannot; an administrative tool to examine what students see and interact with in the AR world; and ways to individualize lesson plans for students. Teachers and educators agreed on the possible issues with classroom management due to the interactive nature of AR. To address the high management requirements, future work may exploring integrating support for teachers in the AR systems.

6. 1. 1. 3 Design Considerations

Interactivity. Though AR learning systems leverage interactivity to promote engagement and deliver personalized learning experience, balancing interactive tasks and slow-paced reflection is critical. In our participatory studies, teachers noted the importance of interactivity, and agreed that children would lose their interests quickly without sufficient opportunity to interact with the visual content and explore ideas therein. For example, with ARMath, direct interaction with physical objects could promote children's kinesthetic learning. However, teachers pointed out potential issues related to excessive attention, fatigue after long-time use, and training efforts for the unfamiliar user interface. For example, a teacher stated "*children may focus too much on manipulative and the tool instead of their thought process or conversations with peers or adults.*" Relatedly, a common concern raised was about low cognitive engagement with learning. Children could perceive the AR learning experience as merely play or game due to rich visualization or interactivity. We suggest instructional or systematic facilities that can let students be aware of the fact that they are indeed learning specific topics in school curricula. For example, the system may ask children to select a specific learning goal or provide sample lessons to ensure achieving the learning goal.

Engagement factors. We have identified from our studies the following elements of children's engagement: physical interaction, creativity, and life-relevant contexts. The SharedPhys designs involve physical interactions such as whole-body postures to investigate inner body parts from different perspectives, physical activities to test its effect on physiology, and gestures to perform a game. When using their bodies, children became attentive and took ownership of an on-going learning activity. The trend obtained in the preference for the designs was also towards designs requiring higher levels of physical interaction. A significant finding in the PrototypAR's study for children's engagement is that children used paper craft for prototyping models, and therefore may implement and test their creative ideas. They enjoyed having this level of control in their design and experimentation process, which led to engagement with design iterations and unexpected findings. In ARMath, everyday objects, life-relevant actions, and virtual storytelling combine to create a familiar context in which children actively participated in meaningful math tasks.

Scaffolds design. The inherent properties of AR visualization such as presence and immediacy make it suitable for providing learning support—that helps children perform STEM practices and achieve learning goals. The design of scaffolds, especially the computer-mediated ones, needs careful considerations with respects to attention, contexts, user control, and goals. We suggest designing scaffolds through the participatory design process where we can understand children's challenges in performing the learning tasks, understanding visualizations, or attaining the learning goals. In design of scaffolds, a virtual agent that children can interact would be useful to not only provide feedback and knowledge but also engage them in the immersive experience and learning tasks. We recommend several design considerations for such agents including: children-friendly visual appearance (*e.g.,* a monster in ARMath), verbal communication (*e.g.,* dialogues or Text-To-Speech), and emotional connection with children (*e.g.,* asking for a help).

Our research explored three types of scaffolds with different purposes including: (i) supportive scaffolds to provide domain knowledge as needed; (ii) strategic scaffolds to guide learners through the process of STEM practices; and (iii) procedural scaffolds to help learners use the unfamiliar AR tools. For example, in PrototypAR, children with less knowledge actively made use of design feedback superimposed on an on-going prototype to build a complete model. They also divided and conquered the high complexity of a design by following the strategic scaffold illuminating and constraining the physical work area. In designing ARMath prototypes, teachers emphasized the affordance of AR to visualize otherwise invisible math knowledge such as arithmetic procedures, abstract concepts (*e.g.,* set), and geometric primitives. In our study, virtual representations alongside concrete physical representations, overlaid by symbolic notation (e.g., "÷" operator) prompted math discourse and supported children's sense-making efforts. Also, children engaged with interactive tools (*e.g.,* a virtual protractor) to find and examine math solutions.

6. 1. 2 The SharedPhys System

A contribution of this dissertation is the design, development, and evaluation of SharedPhys, a room-scale mixed reality system that integrates physiological sensing, whole-body interaction, and large-screen visualization to support collaborative inquiry learning and embodied interaction. The research involved: (i) designing user interface and learning activities through participatory design sessions, (ii) developing the three prototypes integrating the computer vision, sensing, and graphics technologies, and (iii) evaluating the prototypes with children. The three-part investigation provides empirical evidence and useful design implications around the key features of physiological sensing, whole-body interaction, and large-screen display

Physical interaction. Integrating vision-based body tracking and physiological sensing enables new types of embodied learning activities, allowing for children to interact both explicitly (e.g., gesture, movement) and implicitly (e.g., changing breathing rate). This heightened physical interaction promotes children's engagement with learning activity, collaboration between wears and non-wears, and non-verbal social interactions. For example, children enjoyed performing a unique whole-body interaction for each prototype to investigate different aspects of the human body—*e.g.,* turning left and right to view body organs from different perspectives or jumping to see how a chicken breathes fast. While wearers were engaged with physical interactions, non-wearers support them by observing, recording, and reflecting on the wearers and visualizations. In the meantime, they communicated with others to suggests a physical action, encourage wearers, or mimic other's ideas. The unique setup of SharedPhys which support physical interactions in a shared, mixed reality environment enables playful and collaborative embodied learning.

Physiological Sensing. Physiological sensing can be an engaging and personally meaningful interaction technique in mixed-reality environments. We posited that integrating the body data into AR visualizations can engage children in interacting with the AR learning content and promote the relevance of learning. Indeed, children enjoyed manipulating their virtual avatars' physiology by performing physical activities. Though we did not quantitatively measured the relevance of learning, our observations and the program staff interviews indicate the benefits of promoting personalized learning. However, our work leaves limitations to the sensing technology in terms of usability and scalability. Accurate physiology sensing requires invasive sensors that involves discomfort and time to put on, and sensors designed for adults may be unsuitable for children. The communication scheme of sensors limits the number of concurrent participants, for example, by 6 in our research.

Large-screen Display. Our approach of a room-scale AR that using a large-screen display and the mirror interaction metaphor allows children to perform the tasks of carrying out experiment and analyzing the data at the same place. Advancing prior sensor-based learning in which students explore retrospective activity data, the integration provides a more engaging platform where children can conduct collaborative data-driven inquiry. However, the shared and collaborative nature of display may have limited personalized learning as it requires all children to interact with the same data and representation. Also, allowing access for others' data has the potential privacy issues.

6. 1. 3 The PrototypAR System

The second major contribution of this dissertation is the design, development, and evaluation of PrototypAR that allows children to prototype complex systems using familiar paper crafts and test them in a virtual simulation environment. The research involved three steps including (i) conducting participatory design studies to iteratively design and refine the user interface; (ii) developing the PrototypAR system and three applications for complex systems learning; and (iii) evaluating the system to uncover opportunities and challenges of our approach. Our work demonstrates the potential of AR approach for complex systems learning, providing empirical evidence and design implications for free-form tangible interaction and AR visualization for scaffolding.

Paper Craft. The tangible interaction using the free-form material enables lightweight creation of virtual models, facilitating representation of children's ideas and collaborative learning. Because our approach uses craft paper already familiar to children, children engaged in the iterative process of creating and testing virtual models, examining their ideas. They also explored a breadth of designs, generating distinct models useful for following comparative experiments. This creative approach offers children a learner-centered environment where they have control in addressing their unique interests and deepen understanding, which could led to unexpected learning outcomes. However, the free-form construction may have limited opportunity to example all the parts of a target model and develop holistic understanding about it. Future work may explore scaffolds for guiding their efforts to design and execute systematic modes of inquiry. While the shared-physical space promoted children's collaborative design, the relatively small virtual interface makes it hard for children to manage conflicting ideas in experiments.

AR Scaffold. The AR-mediated scaffolds are effective for providing immediate design feedback and helping with the complexity of a design, however, children were less likely to engage with scaffolds suggesting design ideas or tasks. As PrototypeAR actively recognizes and evaluates a physical model, it can provide in-situ scaffolds needed to improve the design. The immediate presence of scaffolds was critical for children to grasp needed actions or corrective advice for the physical design. Our work only begins to explore providing scaffolds via AR visualizations, resulting in the following design implications: (i) children need to have control over when and what scaffolds are given; (ii) Second, a visual overlay can be effective for managing complex tasks; and (iii) scaffolds for suggesting ideas or directions should include a systematic feature to at least capture children's attention and let them follow.

Complex Systems Learning. Our work advances tools for complex systems learning by exploring an AR approach for interactive modeling and simulation. Our tangible approach is suitable for young learners, eliminating the needs for tangible artifacts or programming. The AR scaffold helps children build the structure of a complex system. The accompanied virtual simulation allows children to learn about functioning of complex systems through observing AR simulation of component behavior and comparing the functions of different designs. These approaches combine to lower barriers to modeling and experimentation of complex systems. However, our work is limited in its design capability to support more complex models involving large number of components, immersive experience due to the distributed physical and virtual spaces, and evaluation to examine the learning outcome.

6. 1. 4 The ARMath System

ARMath contribute to the development of mobile AR system that support discovering mathematical concepts in ordinary objects and engaging with math problems in meaningful contexts. To design ARMath, we employed a human-centered approach involving: (i) four participatory design sessions with teachers and children; (2) the implementation of a mobile app integrating computer vision and AR visualizations; and (3) an exploratory evaluation with children using five elementary math learning contents. Bringing these investigations together expands the design space of mobile AR for math learning, first in the tangible user by exploring opportunistic use of everyday objects, second in the affordances of AR by integrating storytelling and AR scaffolds, and in the understanding of children-AI interaction.

Tangible Interaction with Everyday Objects. The tangible interaction with everyday objects promotes children's engagement with mathematical discovery and arithmetical operations. We identified the engaging attributes including: using familiar objects, life-relevant actions (*e.g.,* dividing chocolates), and visualizing objects' mathematical attributes. Children's comfort and familiarity with everyday objects could motivate children to challenge them with a harder problem involving many objects and explore new mathematical ideas in the surrounding environment. Also, blending mathematical practices into everyday experience could encourage their confidence by allowing for solving otherwise difficult math problems on their own. However, in comparison to the virtual/touchscreen interface, the direct tangible interaction offered less opportunity for collaboration as children rapidly manipulated physical objects with less reflection or discussion.

AR affordances. Throughout the design process, we explored in what ways AR can engage children in math learning. AR storytelling presenting a meaningful situation involving math ideas, visualization of abstract equations for the on-going tangible manipulations, and AR tools enabling math tasks were found to key elements to motivate and facilitate children's math discovery and problem solving. AR storytelling accompanied with physical imagery and word math problems could create a life situation where children were motivated to think about applicable math computations or concepts. Children also emotionally engaged with the narrative of helping a virtual agent solve math problems. Presenting abstract equations alongside the tangibles could trigger children's interests on formal symbolic math and after children opportunity to practice translating concrete mathematical representations into abstract forms. Lastly, the interactive tools such as counters and protractors could engage children with the basic math skill of counting and measurement.

Child-AI interaction. Our study rARelated to children's reactions, attitudes, and efforts to repair AI errors has design implications for child-AI interaction including: (i) children are willing to understand and fix AI errors; (ii) Children react differently to types of AI errors; and (iii) repairing AI errors can afford children a new opportunity for learning. When recognizing errors in the virtual agent's description, children tried to understand AI behaviors and adapt their interaction to the system's technical limitations (*e.g.,* not detecting occluded objects). With the repairing AI interface, children were willing to help fix false-negative errors demonstrating sympathy with "mistakes". However, they reacted negatively to false-positive errors thinking that the AI was lying. This split reaction can be attributed to children's tendency to see AI as like a person. Interestingly, some children recognized that they learned from repairing AI errors. The awareness of potential AI errors and the explicit repairing step could

6. 2 Future Work

We describe the limitations of this dissertation, how future research may address them, and directions for expanding our work. Specifically, we discuss: (i) design tools for facilitating designing AR learning experiences, (ii) use of immersive AR devices such as a head-mounted AR goggle, (iii) future user interaction techniques, and (iv) learning evaluation.

6. 2. 1 Design tools for AR

Across the three threads of research, we employed an iterative and participatory design process that involved adult educators and children as co-designers. To help design learning activities and user interfaces, we conducted hands-on design activities of group sketching, lo-fi prototyping, and iterative testing. Though this approach allowed us to gather the participants' ideas and feedback, both adult and children designers faced difficulties in translating creative concepts and instruments into AR experiences. The unique AR features—e.g., inclusion of virtual content in the physical environment or user interaction with virtual objects—were hard to represent on traditional design materials (*e.g.,* visual slides and tangible props).

Future work may explore authoring tools for AR, which may allow novice users to design education-oriented AR applications. Aside from AR development toolkits (*e.g.,* Vuforia and ARCore) requiring significant programming skills, there are GUI-based AR authoring tools for non-programmer. However, the existing tools such as Wiarframe and Torch AR focus on merely supporting association of physical markers and virtual objects. The future AR authoring tools would support the following features: 1) defining types of AR user interactions and feedback; 2) describing user flows along with triggers and transitions; 3) simulating user experience; 4) guiding design in a structured framework to include instructional features such as scaffolds and assessment; and 5) providing a high-level programing environment (*e.g.,* visual block-based programming[14]).

6. 2. 2 Immersive AR

Our research explored conventional displays for AR environments including a room-scale large screen, a smart desktop, and mobile. These environments involved usability issues related to hand-eye coordination and discrepancies between the user's perspective and the AR view as well as limited immersive user experience. Advanced AR devices such as *HoloLens* or *AR glasses* could address these limitations and offer practical use cases.

Other researchers have begun to explore how the immersive AR may improve learning environments. For example, *Chen* et al. [45] evaluated a Hololens-supported AR learning against a traditional learning using slides—in teaching human anatomy and physiology similar to SharedPhys. The study showed promising potential for mitigating cognitive interference (*e.g.,* continuation of extraneous thoughts during the learning tasks) and enhancing self-efficacy. However, the use of Hololens did not have a positive effect on the memory recall of the learning material. Echoing our discussion in Chaper 4.5, future work may explore ways to balance student engagement in the immersive AR environment and accomplishment of learning objectives.

The use of immersive AR devices should need careful considerations due to its potential usability, logistical, and technical issues. Wearing a headset could involve significantly high level of attention and cause discomfort for long-time use. The immersion in the mixed-reality environment could lead to less interaction with learning peers or teachers, which limits collaborative learning. Interactions such as speech commands or hand gesture may be unsuitable for classroom management. The limited and narrow field-of-view would make it difficult to perceive the whole learning environment and look for instructions in information. Future work should investigate how to mitigate these potential challenges by advancing the technology or designing appropriate learning activity.

6. 2. 3 User Interaction Techniques

Our research builds upon and expands user interaction techniques using physiological sensors and computer vision for gesture recognition, visual understanding, and object detection. Exploring new types of sensors and alternative computer vision techniques could help develop novel AR user interactions that can support personally meaningful and engaging learning experiences.

Future work may explore sensor-based user interfaces to support inferring the learner contexts and tracking features (*e.g.,* attention) of a learner as well as gathering relevant data and presenting it to the learner. Similar to our approach in SharedPhys, providing situated visualizations of sensory data—collected from wearables or stationary IoT devices—could afford learners analyze scientific phenomena in their own settings. For example, gathering the amount of noise from the microphone of a mobile devices at a landmark place and augmenting the place with the temporal data could allow learners to investigate the patterns of noise, visitors, or traffic. Environmental sensors such as air pollutants or temperature sensors could also support data-driven science learning. NFC or RFId tags attached to physical objects could allow for precisely tracking user's attention and present learners with relevant learning materials, which helps learners remember factual knowledge associated with objects of interests. The sensors such as EEG or physiological sensors may support personalized user interface based on the inferred status of a learner's emotional state and attention [8].

There are many opportunities to support contextual user interactions by employing advanced computer vision techniques to recognize the learner's environments. For example, semantic segmentation or understanding of visual scenes [292,293] may enable spatial interaction with the environment (*e.g.,* navigating with in a space) or tangible interaction with physical structures (e.g., walls) to access contextual information. Furthermore, people image segmentation and pose estimation technique could support collaborative interaction—*e.g,* a teacher and a student collaborative build and investigate 3D geometry structures [252].

6. 2. 4 Evaluation of Learning Effect

At the end of research, we field-deployed each system to demonstrate the technical feasibility, understand design issues related to AR-supported STEM practices, and examine user experience in terms of interaction patterns, engagement, and preferences. Though our studies generated implications for AR learning systems, they were initial exploratory evaluations and therefore our findings related to learning were limited to demonstrating the learning potential—*e.g.,* performing the steps of inquiry with SharedPhys or making scientific discoveries from experiments in PrototypAR. These findings are insufficient to examine what and how children indeed learn in the AR learning environments.

Other education researchers have investigated learning effects of AR, examining in what ways AR can promote cognitive development or skill acquisition. For example, prior research documented the positive effects such as facilitating development of skills in organizing and evaluating data [145], enhancing understanding of complex causality [232], and gaining more accurate knowledge on the topic [254]. Likewise, future research needs to move beyond AR as an engaging learning platform to examine, for example, how children acquire inquiry skills through the AR-based collaborative learning, how AR-based modeling and simulation contribute to enhancing knowledge about a complex system, or whether the AR-supported mathematization improved children’s arithmetic skills or formal symbolic math.

Appendices

1. SharedPhys Demo Video
2. SharedPhys Study Materials
3. PrototypAR Demo Video
4. PrototypAR Study Materials
5. ARMath Demo Video
6. ARMath Study Materials

1. SharedPhys Demo Video

Video Link: https://youtu.be/eRIO4AzPd8s

2. SharedPhys Study Materials

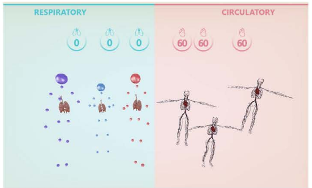
makeability lab

Post-Activity Questionnaire

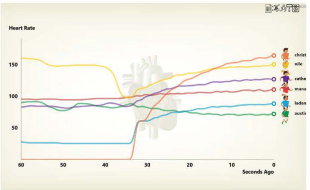
Human-Computer Interaction Lab

Name: ____________________ Age: _____ Grade:_____ Are you a boy or girl: _________

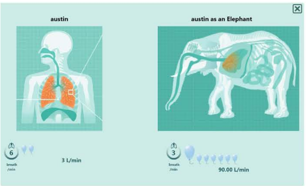
1. Today, you used three different designs: Magic Mirror, Moving Graphs, and Animal Avatar. Please **circle** your favorite design below.



Magic Mirror



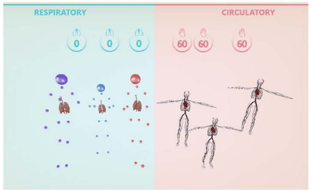
Moving Graphs



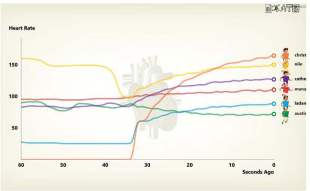
Animal Avatar

2. Why was that design **your favorite**?

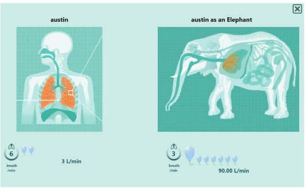
3. Please **circle** your **2nd favorite** design? (Do not circle the same design as above).



Magic Mirror



Moving Graphs



Animal Avatar

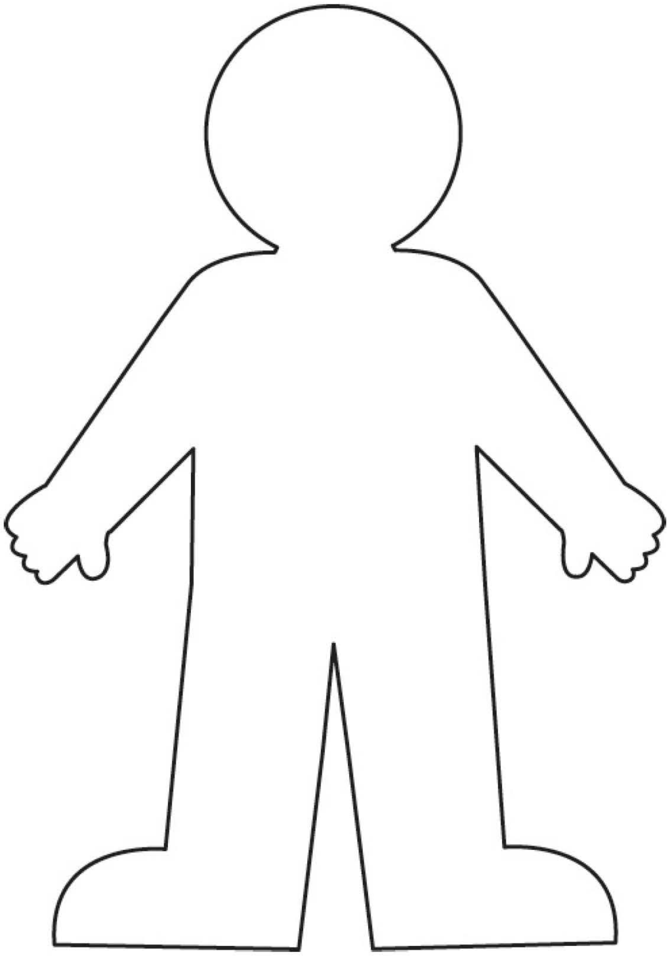
4. Why was that design your **2nd favorite**?

5. Check one. I had **fun** participating in today's activities and learning about the body.

Very Fun	Some Fun	Neutral	Hardly Any Fun	No Fun
○	○	○	○	○

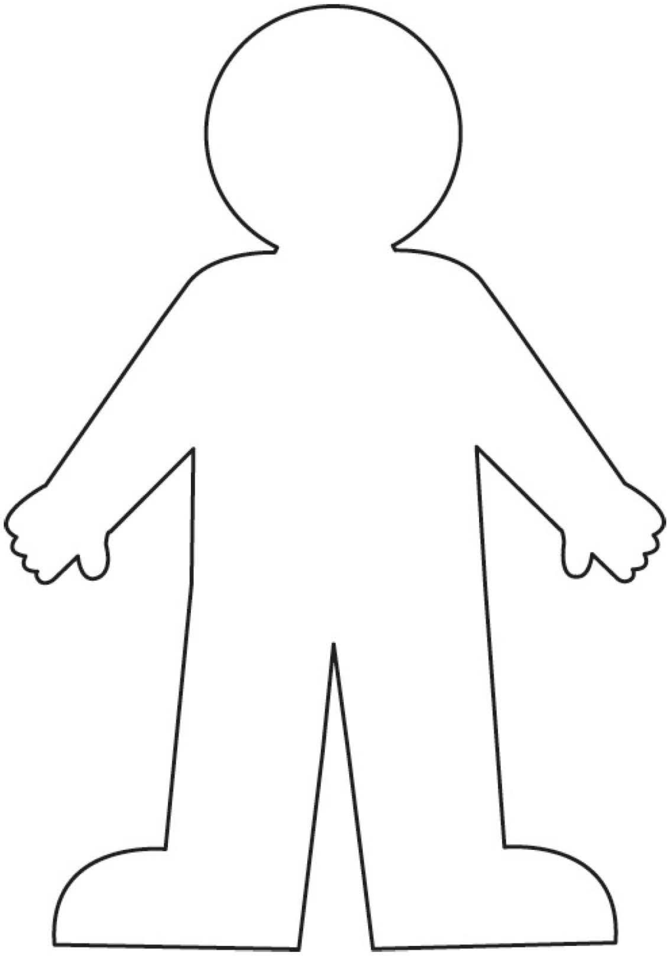
6. Just like before, draw all of the organs and body parts you can think of that are part of the **respiratory system** (the system that helps you breathe). Draw each body part the way you think they look. Be as specific as you can. Please **label each organ** with the **name** and **function**.

Draw Your Respiratory System



7. Now draw all of the organs and body parts you can think of that are part of the **circulatory system** (the system that helps blood move around your body). Draw each body part the way you think they look. Be as specific as you can. Please **label each organ** with the **name** and **function**.

Draw Your Circulatory System

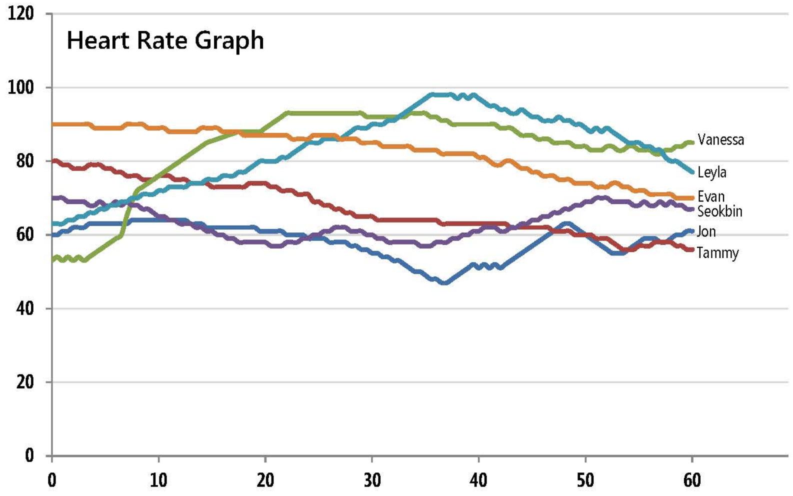


8. **Fill in the blank.** Air moves from your nose or mouth down through your airways and into your _______________________. When you breathe, your _____________________ moves air in and out of your lungs. Your muscular ____________________ pumps blood

through your ______________________. Blood returns to the heart through your

________________________.

9. Using the graph below, whose heart rate reached the **highest point** in the last 60 seconds? **Circle the correct name:** Vanessa Leyla Evan Seokbin Jon Tammy



10. Using the graph above, whose heart rate reached the **lowest point** in the last 60 seconds? **Circle the correct name:**

Vanessa Leyla Evan Seokbin Jon Tammy

11. If you had to estimate the **average group heart rate** in the last 60 seconds, what would be the closest estimate to the correct answer. Circle one.

A. 30 heartbeats per minute
B. 50 heart beats per minute
C. 70 heart beats per minute
D. 90 heart beats per minute
E. 110 heart beats per minute

12. What is your **resting heart rate**? An estimate is fine: __________ beats per minute

13. Why does your **heart rate** and **breathing** rate **increase** when you exercise?

14. Check one. I find **learning** about my body and body organs…

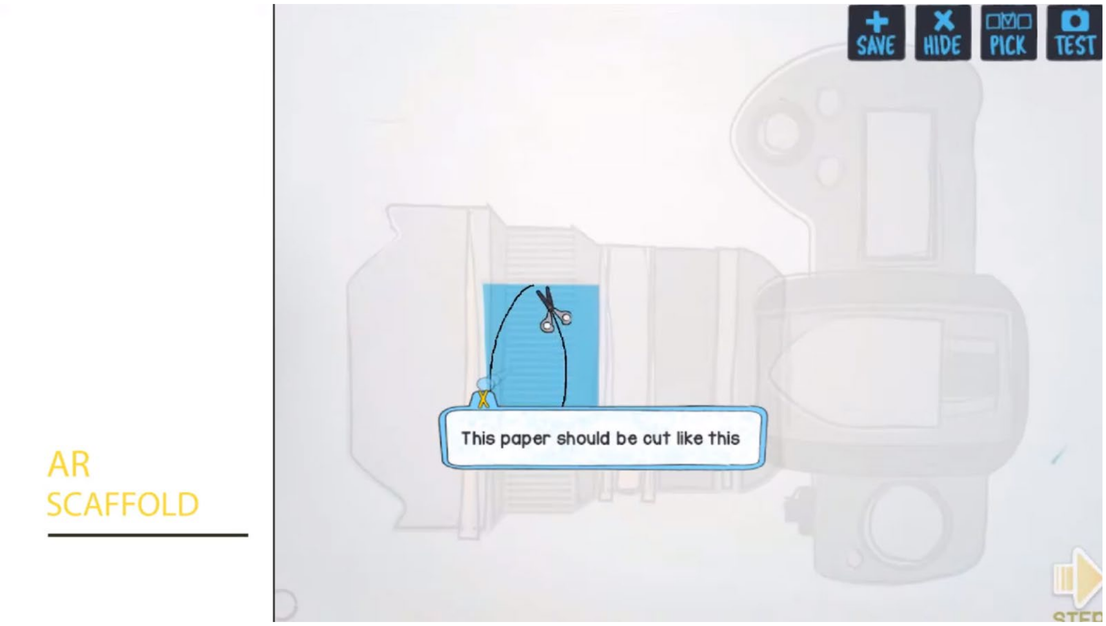
Very Interesting	Interesting	Neutral	Boring	Very Boring
○	○	○	○	○

15. Check one. I think it's important to **understand how my body works**…

Very Important	Important	Neutral	Not really Important	Not at all Important
○	○	○	○	○

16. Fill in the blank. The **circulatory** and **respiratory systems work together** to deliver _____________________ to the body's cells and tissues and to get rid of the gaseous waste called __________________.

3. PrototypAR Demo Video



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Video Link: https://youtu.be/jt9oqqWZHFk

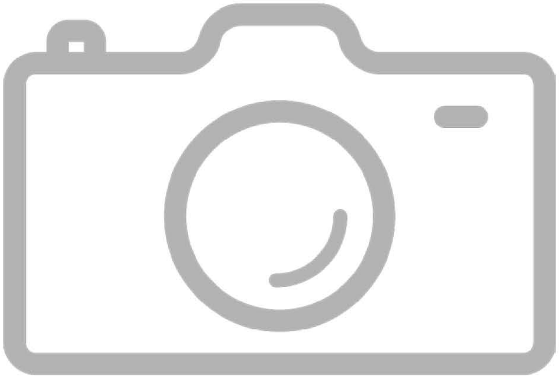
4. PrototypAR Study Materials

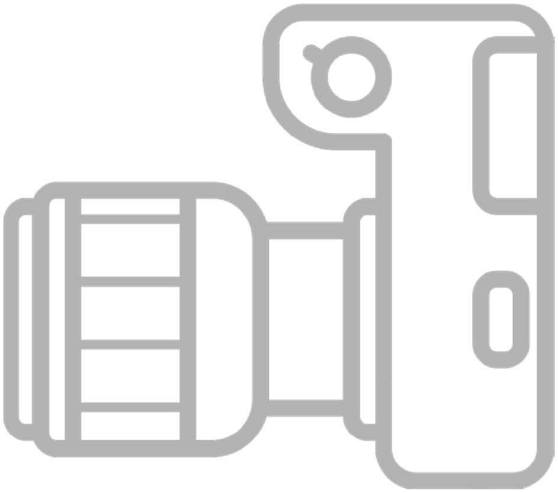
Rainbow

Pre-Activity worksheet (5 min)

Name: ____________________ Age: _____ Grade:_____ Gender (circle one): Boy / Girl

1. Draw all the **parts inside camera** that you know. Draw them the way you think they look and add names..





Rainbow Post-Activity Sheet (5min)

1. I had fun using Rainbow

2. I think the Hint (? HINT) was helpful

3. I think the Test (TEST) was helpful

4. I could create different cameras easily

5. When I tested cameras, I could see difference between them in photos

Rainbow

Focus Group Interview Questions (15min)

1. What did you learn from using Rainbow?

(Follow-up) What about cameras?

2. What is your favorite part of Rainbow? Why?

(Follow-up) What is your least favorite part of Rainbow? Why?

3. Did you make any mistakes when designing your cameras? (related to camera design)

(Follow-up) How did you know that (the mistakes)? How did you fix that?

4. Do you remember the Hint button?

(Follow-up) Do you think it is helpful? Why?

5. Do you remember the Test button?

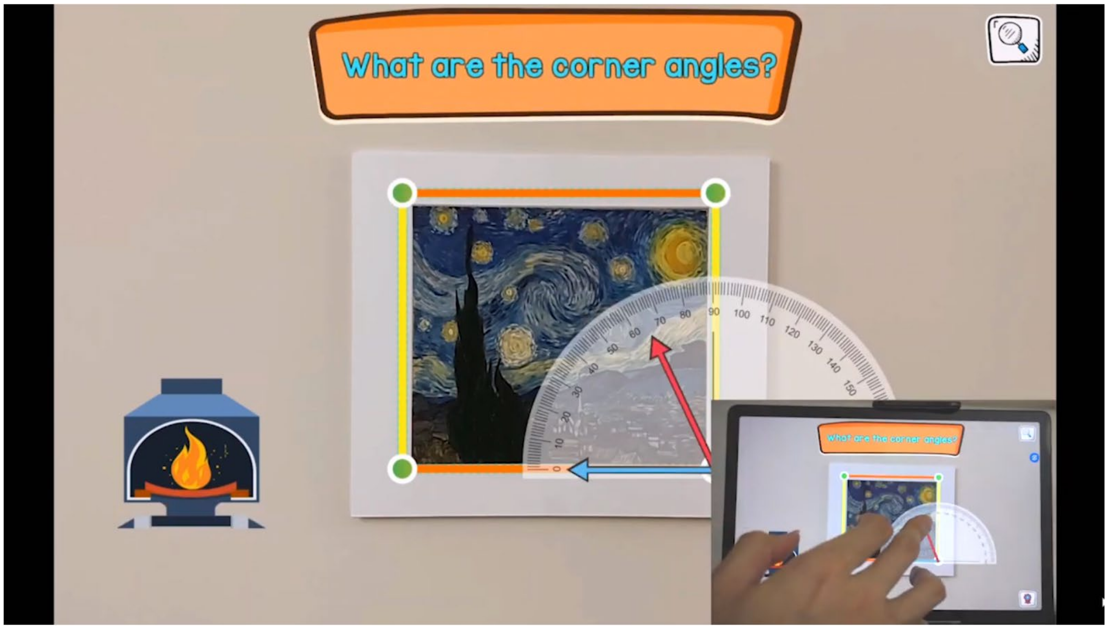
(Follow-up) Do you think it is helpful? Why?

*EXTRA QUESTIONS

- Do you think Rainbow is easy to use?

-What would you like to design with Rainbow?

5. ARMath Demo Video



Video Link: https://youtu.be/nUC0toUJZUk

6. ARMath Study Materials

ARMath Pre-Activity worksheet (5 min)

Name: ____________________ Age: _____ Grade:_____ Gender (circle one): Boy / Girl / Other

1. I like doing math

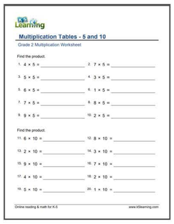
2. I think math is important throughout life.

3a. I like using blocks and toys to learn math

3b. I use blocks and toys to learn math

☐Everyday ☐Every week ☐Every month ☐Never used

4a. I like using pencil and paper to learn math



4b. I use pencil and paper to learn math

☐Everyday ☐Every week ☐Every month ☐Never used

5a. I like using a <u>computer</u> to learn math

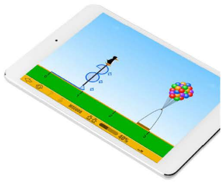
5b. I use a <u>computer</u> to learn math

☐Everyday ☐Every week ☐Every month ☐Never used

6a. I like using <u>a tablet or a phone</u> to learn math

6b. I use <u>a tablet or a phone</u> to learn math

☐Everyday ☐Every week ☐Every month ☐Never used



7a. Find the missing number.

a. 5 + 4 = ☐

b. 9 – 4 = ☐

c. 8 ÷ 4 = ☐

d. 3 x 5 = ☐

7b. Draw a “rectangle” below

ARMath Post-Activity Sheet (5min)

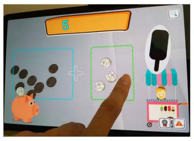
1. I think using ARMath app is fun

2. I think ARMath helps me learn math

3. I would like to use ARMath at home or school

4. I like using real objects on the table in ARMath

5. I like using icons on the screen in ARMath



ARMath

Focus Group Interview Questions (15min)

[General Follow-up Questions]

- Why do you think so?
- Can you tell me more about what happened?
- That's so interesting, can you tell me more about?
- What is there about the…?

0. Ask follow-up questions for the Likert questions

1a. What is your <u>favorite</u> part of ARMath?

1b. What is your <u>least favorite</u> part of ARMath?

2a. What do think you learned about math today?

2b. What other things would you like to learn with ARMath?

2c. ARMath uses things around us like coins, batteries, chocolates, and paintings. What other objects might be cool for us to use next?

3a. Would you like to use ARMath rather than <u>blocks and toys</u>? Why?

3b. Would you like to use ARMath rather than <u>textbooks</u>? Why?

3c. Would you like to use ARMath rather than <u>computers</u>? Why?

4. Did you find Victor () was wrong about the <u>numbers and objects</u>? Did you like helping him <u>correct the mistakes</u>?

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