NEW MODALITIES AND TECHNIQUES OF AUGMENTED REALITY IN STEM EDUCATION

by

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This thesis is dedicated to my parents, to my brother, to my sister-in-law, to Remy, and to Pia. Thank you for your unconditional love and support.

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PREFACE

Ever since I began my Mechanical Engineering degree at the University of Kansas (KU), I had planned on working in research. My goal during my undergraduate career was to gain a thorough understanding of how to conduct interdisciplinary research ranging from engineering to technology. My freshman year at KU, I started researching along Dr. Lisa Friis, the director of a spine researching lab which is part of the Bioengineering Research Center (BERC). And for my remaining years at KU, I became a permanent undergraduate researcher at the BERC. My main motivation to apply for this position was the opportunity to work with Dr. Paulette Spencer, an eminence in the dentistry community. Here, I worked on projects that primarily involved characterization and testing of the mechanical properties of novel monomers in dental composites.

As a PhD student in the Convergence (C) Design Lab, I decided to continue my focus into human-centered research, but with an emphasis in the technology to improve learning, in the area of human-computer interaction (HCI). Thus, the theme of my thesis was born: Augmented Reality in Education. Throughout my PhD, my research has focused on designing tools to create collaborative learning experiences for project-based classrooms and distance makerspaces. While collaboration has several meanings depending on context, I specifically refer to two or more students being able to complete tasks effectively and simultaneously. This research aims to provide multimedia tools, especially in augmented reality, to instructors and students, in order to facilitate learning in distance classroom settings. I believe that high-quality hands-on learning, in particularly STEM education, should be available to all people, regardless of geographical constraints or availability of resources. Moreover, as distance learning platforms become widely used, it is important that we figure out how to keep students, especially children, engaged. My hope is that this thesis provides valuable tools and ideas into how to provide more natural interactions for distance collaboration.

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ABBREVIATIONS

AR	Augmented Reality
TAR	Tangible Augmented Reality
UI	User Interface
IoT	Internet of Things

ABSTRACT

Emerging technologies in the classroom are paving the way towards high-quality, hands-on distance learning. Augmented Reality (AR), which overlays virtual information into the physical world, provides a promising solution for the development and delivery of collaborative educational content. Frameworks such as ARkit, ARCore, have enabled AR experiences to become available to a wider audience. However, there are still several challenges to implementing an AR-based curriculum in classrooms, such as difficulty to create AR content, lack of an architecture capable of supporting collaboration between users, and questions about the user experience. This thesis introduces the MetaAR project, a series of solutions to enable instructors and designers to prototype AR experiences in collaborative and distant classrooms. We designed and tested interactive systems, each targeted towards solving a different problem: (1) MetaAR, an augmented reality authoring platform for instructors and students; (2) RobotAR, a robotics toolkit to create augmented reality-based makerspaces; (3) ColabAR, a toolkit for quick-prototyping of Tangible Augmented Reality (TAR) laboratories; (4) Grove-Blockly, a website with a STEAM curriculum involving IoTs, crafting and coding aimed at middle-schoolers; (5) Towards Modeling of Human Skilling for Electrical Circuitry using Augmented Reality Applications, which provides a model to cluster microskills found in AR (perceptual, cognitive, motor) and aligns them to educational content design for AR. Our preliminary results, obtained from user studies involving more than 120 participants, provide evidence of the sustainability and the positive reception of our prototypes in learning environments. We demonstrated an improvement in several of students' key competencies and in the overall user experience for both instructors and students. Our hope is that this thesis provides a pathway towards more natural interactions and advances in our understanding of distance learning technology, which is becoming increasingly important in today's society.

1. INTRODUCTION

The rise of new technologies used in classrooms have improved the ways to deliver texts, graphics, animations, video, and other educational contents [1]. The educational market has grown into a multibillion-dollar industry and digital tools are widely used in US classrooms [2]. This adoption translates into an increase in the use of large form displays (e.g., LCD screens, tablets, desktop-computers), multimodal interaction devices (e.g., Kinect, MR head mounted devices), VR (e.g., headsets, goggles), and AR (e.g., headset, phone, tablet-based) technology in classrooms [3]. With the proliferation of these new media and with almost every in-person education program having a remote equivalent [4], we must consider the ways in which we can take the benefits of in-person instruction and translate them into a virtual environment. AR, which superimposes virtual information into the physical world, provides unique hands-on capabilities to deliver educational content. In the last decade, there has been a surge of interest in acquiring knowledge through a minds-on and hands-on approach [5], [6]. An AR display (e.g., a headset, a tablet or a mobile phone) provides the user with an interface to the virtual world, which enables interactions with physical objects. This hybrid approach allows for virtual information to be overlaid on objects and can demonstrate to users what cannot be perceived by their own senses and thus, learned [7] (e.g., pressure, temperature, voltage).

In terms of educational material, AR has been empirically implemented in classrooms for five main applications [8]:

(1) Collaborative and situated learning by students exploring new interaction modalities in the same environment [9]–[12]: e.g., students simultaneously exploring 3D objects in school grounds. (2) Selecting and manipulating 3D objects [13]: e.g., look inside the inner-workings of a system. (3) Providing students with a social fabric to discuss the learning material and change attitudes towards real-world issues [14]–[16]: e.g., students exploring an AR environment of melting glaciers. (4) Visualizing abstract or invisible concepts [17]–[19]: e.g., pressure, temperature, current flow in a circuit. (5) Creating a transition between formal and informal learning [20]: e.g., lecture vs. laboratory experiment.

While the applications of AR technologies are promising, AR adoption in the classroom remains limited [21]. We identified five categories for the challenges and barriers to implementing AR technology in education [22], [23]:

(1) **Cost**: Schools and instructors tend to be cautious of the investment required for implementation, and for the adaptation and the update of new content.

(2) **Hardware**: Equipment, such as the headset, is difficult to wear for long periods of time. In phone and tablet-AR, using QR codes for accurate tracking of small components in the workspace, can have a cumbersome setups.

(3) **AR content creation**: Creating and animating AR assets is time consuming. There is a lack of sequential workflows and exploratory environments for an instructor to easily assemble the material for a class. Also, there is difficulty to create, maintain, and update the learning content once it has been created.

(4) **Collaboration and distance learning**: An in-person classroom environment, which is made up of a network of co-located students. Thus, to mimic this classroom environment, an AR platform has to provide a system architecture which supports collaborative, real-time authoring and sharing of AR content. Also, the platform needs to provide an equivalent alternative to hands-on support from the instructor and to foster interaction between the students.

(5) **User experience**: Instructors and students alike have concerns about how AR adoption will translate into the user experience. This is due to the unpredictable nature of introducing the human into the loop of AR platforms. Likewise, there are still many unknowns involving the technology, in particular, how would instructors go about solving any troubleshooting problems that could arise from the setup. Also, there are questions about how would students respond the AR technology being a complement or replacement for in-person learning.

Our work centers in solutions for (3),(4), and (5). Also, this thesis investigates the role of AR and the effects of implementing our platforms into project-based classrooms, distant laboratories, and remote makerspace experiences. This work is targeted towards undergraduate students who seek a STEM education by combining high-quality multimedia content and a hands-on curriculum. We hypothesize that AR technologies will result in an increase in student engagement [24]; more importantly, we raise other questions:

RQ1: To what extent do AR technologies lead to an improvement in students' learning experience?. If our systems allow learners to meet key competencies, we ask another question from the point of view of the instructor: *RQ2: To what extent do AR technologies enable the instructor to offer timely and on-point instruction during problem-solving?*. Finally, we wonder how an improvement in learning could influence the interactions between instructors and students, in the form of the following question: *RQ3: To what extent do collaborative AR technologies influence students' engagement and interest?*. This thesis explores all these research questions. We aim to advance our understanding of hands-on distance learning, which is becoming increasingly important in today's society. Also, the purpose of this thesis is to pave the way towards more natural interactions between distant users.

1.1 AR as a tool for education

AR has received much attention as a useful medium for educational content [25]–[27]. Much of this attention is due to the development of AR technology, which has positioned it to become widely available by deploying it on tablets and mobile phones [28]. In terms of education settings, empirical studies have shown that AR improves students' learning achievements, learning motivation, and attitudes towards the materials [29]–[31].

Additionally, AR can help students understand new material through multi-sensory learning, which can often facilitate a positive and playful attitude as students learn through playing with the materials [31], [32]. Although educational AR has been mostly used in the context of informal learning, there is some evidence that it can increase high level critical thinking [33] and enhance spatial abilities [34]. In the case of laboratory settings, AR allows students to try out the technology prior to handling lab equipment, perform some experiments within the virtual world, and can lower laboratory costs [35].

As AR transitions from an informal learning tool to a formal learning tool, it is essential that AR content generation can follow some of the traditional principles for multimedia learning contents [36], to avoid some of the typical drawbacks that come with presenting too much information. In an AR environment, students may experience a cognitive overload due to the amount of material and the complexity of tasks [37]. Thus, the next step to improve the quality of AR content, is to provide well-integrated, organized, and pertinent information (e.g., images, annotations, video tutorials) to improve students' learning experience [30]. AR can benefit from properly organizing all learning components, such as overlaid objects and videos, which can help students with improved processing of the learning content [38]. Classroom orchestration principles have been explored and tested to design an AR learning environment (i.e., integration, awareness, empowerment, flexibility, and minimalism) [39]. However, there has been insufficient explorations on how the learning content can be aggregated to, be moderated, and be modified by the students under instructors' supervision.

1.2 AR for robotics

AR technology, which is capable of creating immersive virtual interfaces, has been used for remote control and teleconsulting in human-robot interaction (HRI) research [40], [41]. Past research has explored AR interfaces in order to control the status and to plan robot activity [42]–[46]. These methods enable easy and intuitive manipulation of the robots [47], and facilitate debugging, operation, and mobility. Other AR interfaces in robotics have been used for object modeling and printing [48], education applications [49], [50], and adjustable wearable robots [51].

Additionally, spatial tasks and immersive visualizations enabled by AR are leveraged for telepresence in HRI applications [40]. For instance, AR can enable collaboration between distant users by providing them with the same virtual environment. Along these lines, users can visualize AR content superimposed with instructions or information of spatially-distributed tasks [22].

1.3 Mixed Reality for Remote Collaboration

In recent years, much focus has been placed on remote collaboration in mixed reality (MR) technologies [52]. The purpose of MR remote collaboration is to enhance interaction between users, usually through non-verbal cues, such as haptic feedback, visual cues, annotations, and avatars [53]. Non-verbal cues, in the form of a hand avatar or a pointer [54]–[56], have shown to improve collaboration and performance; while haptic feedback can improve user experience and awareness [53]. Other remote interactions include drawings and annotations, that allow users to look at the content from multiple viewpoints [57]–[60], head pointing [61]–[63], shared video [59], [64], [65], shared gaze [66]–[68], and shared gestures [69], [70]. Another alternative has been to use 3D models to facilitate explanations [71], [72] between users. Similarly, 3D scene reconstruction [59] and 3D combined with 360 video scene reconstruction [73] have been credited with improving collaboration and user experience. Past research aims to address some of the challenges in collaboration, in which participants must be aware of their environment and of their fellow collaborators' presence and context [52].

These multi-modal interactions are meant to enhance collaboration between remote participants and resemble face-to-face scenarios as close as possible. However, these interactions are typically parts of systems that require significant setups, such as projectors, headsets, skeleton tracking. These are each individual technologies and integrating them is complex, which is why an AR platform with remote access has not been successfully developed. In the context of a environments for remote collaboration, we want the setup to be easily available by the distance learners.

1.4 Overview of Contributions

The purpose of this thesis is to design, test, and prototype interactive systems in the form of a series of solutions to enable instructors and designers to create AR experiences in collaborative and distant classrooms. The contributions of this work are as follows:

(1) An AR-based platform which implements the pull-based model to enable real-time collaborative authoring.

(2) A teleconsulting desktop-based robot and toolkit which enables real-time aid by the instructor and AR instructions.

(3) A TAR laboratory toolkit to enable haptic feedback and AR-based learning content to enable distance partners to collaborate.

(4) A platform that provides a comprehensive e-crafting curriculum based on block-based programming and electrical circuitry.

(5) A model for human modeling of (micro)skilling which introduces embodied cognition theories and methods into the AR research discourse.

Each contribution is presented in a research paper and has its own chapter in this thesis. Chapter 2 introduces MetaAR, a platform which combines the capabilities of cloud technology and adapts the pull-based model, a collaboration workflow to upload, share, and download information for an AR authoring platform. This project is tested for usability with 52 students. Chapter 3 introduces RobotAR, our toolkit to implement a teleconsulting desktop-based robot in AR makerspaces by enabling mobility and translational joints from the robot to better focus on areas of interest inside the workspace. This project is tested for usability and learning improvement with 24 participants. Chapter 4 presents ColabAR, a toolkit for prototyping of AR laboratory experiences. This work implements a remote collaboration architecture supports sharing of AR content and haptic feedback. We conducted two user studies with 40 participants to validate usability testing and learning improvement. Chapter 5 implements a platform which deploys an e-crafting curriculum using the circuitry kit "Grove". This curriculum introduces middle-schoolers to several actuators, sensor, and the Arduino board. This chapter also provides valuable insights into the knowledge space required by students to master basic electrical circuitry and programming. Chapter 6 introduces Human Skilling, a modeling approach to implement knowledge segmentation of a subject area into an AR-based curriculum for basic mastery of a skill. There have been many research projects on using AR in educational settings, but those projects tended to focus on the form factor of AR (e.g. comparing learning gains out of the same education contents with-versus-without AR) rather than the design of educational contents for AR. However, new interaction forms require new information design considerations. Finally, Chapter 7 will have summary and findings from this thesis.

2. METAAR: AN AUTHORING PLATFORM FOR COLLABORATIVE AUGMENTED REALITY IN STEM CLASSROOMS

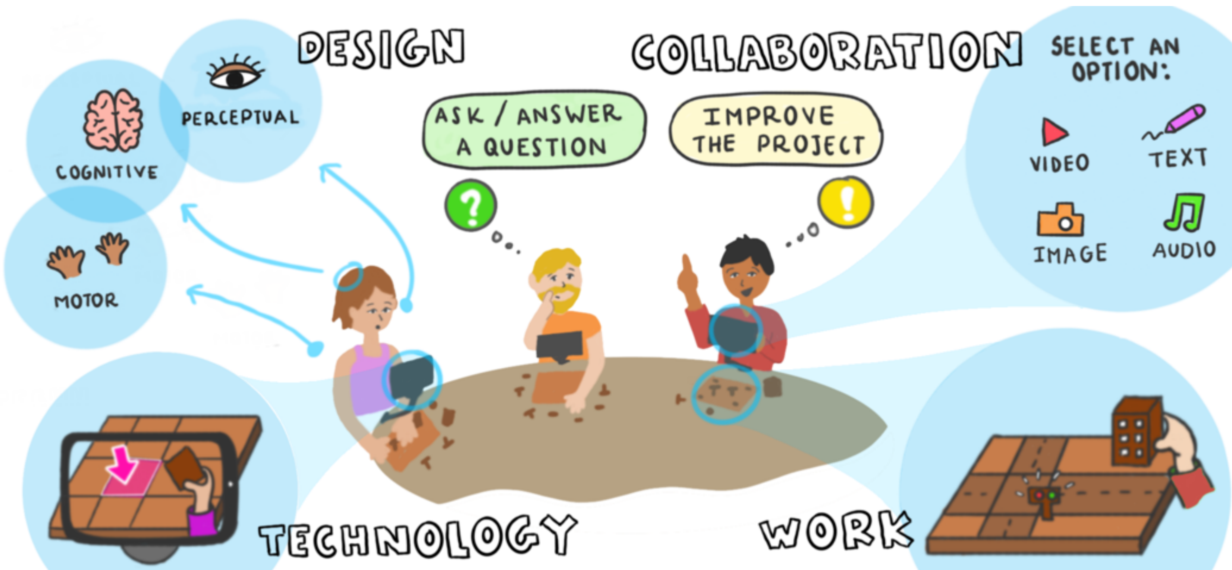

Figure 2.1. Overview of the four category model from a STEM classroom which implements our MetaAR platform: (a) Design: creating learning content (perceptual, cognitive, motor); (b) Technology: effective learning and problem solving using AR; (c) Collaboration: contributions between instructors and students and improvement of learning content; (d) Work: facilitating and empowering discoveries by manipulating tangibles.

This chapter is presenting work published at the ACM CHI Conference on Human Factors in Computing Systems [22].

A collaborative classroom facilitates instructors and students to work together towards solving project-oriented lessons and engaging in different types of interactions. These interactions allow them to answer each other's questions and empower sharing and clarifying the learning content. Thus, it follows that any software targeted to an educational experience has to be tailored towards enabling and moderating these interactions in the classroom. We propose combining AR with the capabilities of cloud technology to introduce the *pull-based collaborative model* [74], a collaboration workflow to upload, share, and download information (i.e., AR content). Students can improve the learning content by adding contributions to the original project created by the instructor. Then, we further customized this workflow to fit the needs of a classroom by creating two types of interaction to moderate the flow of AR content contributions: *local* (i.e., one-to-one student content share) and *global* pull (i.e., instructor approves a student's contribution to the original project given to the class). We envision local pull to be used during class, so that a student's request can be answered by a fellow student, thus relieving some of the burden from the instructor; while global pull can be used after class, when the instructor has had a chance to look through all the contributions made by the students, and determine which ones are the most appropriate to add to the class material. The presence of a moderator (i.e., the instructor) is important to pick the most valuable information to share with the entire class.

We design, develop and assess MetaAR (Fig. 2.1), and present the following contributions from our work:

(1) An **AR-based teaching and learning tool** that supports a STEM educational curriculum by enabling easy-authoring and iterative improvement of class material.

(2) A **collaborative workflow** which leverages cloud technology and supports synergistic interaction modalities between instructors and students inspired by the pull-based development model.

(3) Based on our user studies, we organize a **four category classroom model** for teaching and learning in a classroom with our technology.

2.1 Related Work

In this section we will explore the use of multimedia in education, more especially the combination of AR and cloud technology, robotics, vibrotactile sensors, and learning sciences. We will mention existing work and explain how our work is different from past research.

2.1.1 Authoring Tools for the Classroom

This section describes existing tools we explored to benchmark the MetaAR platform. By doing so, we were able to understand how to create an AR authoring platform which could complement a project-based classroom and the instructors.

2.1.2 Authoring Tools for AR

Existing platforms such as Unity or Unreal are comprehensive game engines that come with a visual editor and allow assets such as 3D/2D models to be imported and managed [75], [76]. While these platforms are preferred by developers and engineers, educators would require an entire new set of skills, such as coding, modeling, or animation, to author AR content. Thus, creating interactive behavior of the AR assets remains difficult [77]. The vast majority of AR authoring solutions have concentrated on assembly research, ranging from context-aware systems using engineering ontologies [78], [79], automated instructions using computer vision [80]–[87], linking systems using existing multimedia platforms [88]–[90], interaction methods or plugins on top of other platforms [91]–[96], and hybrid systems pursuing a combination of the aforementioned [97]–[104]. These platforms were constructed to solve specific issues, and to allow different methods of human input in the authoring process. However, given their focalized scope, they allow for limited interaction and scale. Also, they do not support real-time modification of displayed content. Some commercial solutions for general applications, such as Layar, Vuforia Studio or Blippar [105]–[107], have opted for visual interfaces to make the interaction process easy and intuitive, but the capability is limited and isolated, because they are not meant to be deployed for classroom activities. They lack real-time authoring for instructors and students. Furthermore, they do not support an architecture that enables collaboration and interaction among peers. These features are the baseline for an accessible AR-enabled learning environment. For effective learning, an AR platform also needs to subscribe to the rules of multimedia learning, such as supporting the segmentation of information in bite-size pieces, the division of instructions in auditory or visual channels, or the elimination of extraneous material [36]. MetaAR simplifies much of the authoring process by automatically generating animation pathways, segmenting the task information into bite-size pieces, and allowing real-time modification of AR content. Additionally, our platform explores the landscape of project-based STEM classrooms, which means that the AR authoring technology needs to cater to a learning-while-making approach, such as facilitating trial and error authoring efforts and efficient debugging made possible by iterative authoring of learning content.

2.1.3 Collaborative Tools in the Classroom

Collaborative AR technology must be built to integrate the physical environment, while providing the opportunity to share virtual objects as information, such as annotations, text, videos, and images as supplementary elements between stakeholders (i.e., students, teachers) to investigate their classroom surroundings. However, if we have multiple stakeholders working together collectively and simultaneously on an original project, we need to effectively manage these external contributions to enable conflict resolution by leaving decision-making to a moderator [108].

Other popular non-AR workflows for information sharing in the classrooms have enabled asynchronous [109], [110] or parallel collaboration [111], which has similarly allowed students to read, edit, update content structure between users. However, asynchronous or parallel editing would not work well for an AR classroom [112]–[114] because the information would not be time-sensitive and multiple people could simultaneously modify one step of the project, which would create conflict and cause confusion among students (e.g., use of Google Docs).

In open source software (OSS), pull-based development model implements collaboration schemes to streamline the integration of contributions to projects [74]. The pull-based development model became popular within the open source community with platforms such as GitHub, the largest coding repository site for programmers [115]. The typical pull-based model includes: integrators (project creators) who receive contributions from other members (individual software developers) upon pull request and determine whether to merge content based on technical merit or trust [116], [117]. An adaptation of this particular collaboration model would work well in a classroom setup because it is based on version control, which was specifically designed to resolve conflict among multiple changes and multiple stakeholders.

2.2 Formative Study and Design Goals

To understand how an AR-based platform could support a STEM classroom environment for instructors and students, we shadowed a weekly 3-hour session of a circuits and electronics project-based class in which students built their own robots over a semester period. The observer team was made up of 3 to 4 members, who would take notes and pictures of the

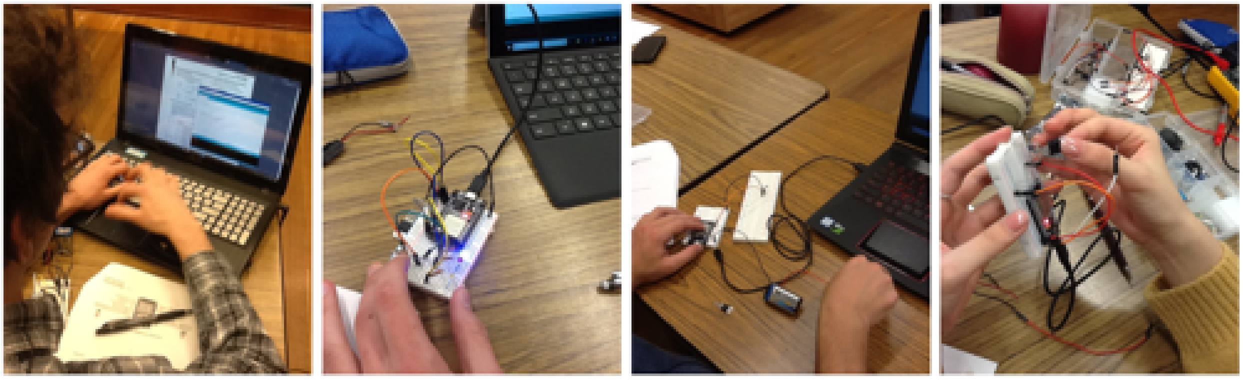

Figure 2.2. Snapshots taken from circuits and electronics class. We documented students trouble-shooting their circuits.

class sessions to create a scrapbook of the collected material (Fig. 2.2). The session was led by two graduate teaching assistants with a high level of subject matter expertise, and attended by ten undergraduate sophomore students. Both instructors had prior experiences in creating AR applications, although no augmentation was used in the class. The themes involved voltage, current, basic electronic components, and Internet of Things (IoT) prototyping. The two instructors reported that it took them ∼3.5 hours per week to create the student manuals for the class–made up of written and graphical instructions–out of which ∼1 hour was spent outlining the content, while ∼2.5 hours were spent creating the content. Additionally, we met with the instructors for a 2-hour session prior to class, in which we became familiar with the project manuals. We choose this class because it perfectly illustrates the benefits of augmentation in a spatial task. In the initial classes, we focused on documenting students' behavior, particularly key points at which they were stuck on the material, their realizations and trouble-shooting, and how they interacted with each other and the instructors. Each week we requested the instructors to describe at high level how they would create the learning content using AR and what visual aids (e.g., highlighters, animations, etc.) would improve the experience. Based on our observation of the class, we concluded with a set of design goals to create our system:

2.2.1 Three Main Types of Microtasks in AR Authoring

The instructors identified three types of microtasks to be included inside the steps from the student manuals: (1) visually-oriented microtasks, which can be accomplished by singling out an object (e.g., highlighter) and focusing the student's attention in a particular direction (e.g., arrow), (2) knowledge-oriented microtasks, where the students encode information to understand the instruction, which has to be delivered in a longer format (e.g., textbox, annotation), and (3) spatially-oriented microtasks, which request motor performance and require expert demonstration (e.g., animation, tutorial). These insights were consistent with the human processor model [118], which encodes human processes as perceptual (i.e., visual), cognitive (i.e., knowledge), and motor (i.e., spatial), and inspired the features of our authoring toolbar: each animation step can include a microtask, which can be authored using a suggested set of tools, while the objects can be placed and moved in the scene through our drag-and-drop interface.

2.2.2 An Efficient Collaboration Process

Observations from the class made obvious that students can contribute with new or improved content, especially since not all students work at the same pace, and some students may notice unclear or missing instructions ahead of the rest of the class. We noticed that ahead-of-the-curve students tried to demonstrate their realizations to those around them, but were often impeded due to the information being lost as other students were steps behind and failed to register the aid. A classroom environment is unique in that the students are co-located and that instructors should be capable of moderating the quality of information, so as to filter mistaken additions or changes. We were inspired by the pull-based development process typically used in software development and successfully implemented in software engineering courses [108]. We adapted the process to work in our AR-creation context by providing the instructors with moderation capacity (i.e., decide which content to change or merge), and the students with the option to create and pull content that does not overlap with their already completed work.

2.2.3 High Adaptation for a Variable Environment

Unlike other multimedia tools, AR is heavily dependent on the environment available for exploration. In the class, we observed how students increased and worked with a wide variety of components, tools, and materials; however, the concepts, knowledge, and rules for working with them, were similar across the board. Thus, in order to save resources and cost, we can recommend instructors working with simple, cheap, and generic components that can be used by students (e.g., a microcontroller), while the augmentation can provide for more complex variations of these components and different phenomena.

2.3 The MetaAR Framwork

Early in the decision process, we realized that the only way to make MetaAR an appealing tool for a classroom environment was to simplify the implementation process, so as to avoid placing an extra burden on the content creator, taking away time from the actual class preparation. Our back-end algorithm allows the user to navigate all the features of the system widgets, which eliminate extraneous steps to create, share, and interact with the learning content. For example, our drag-and-drop interface enables creating an animation by selecting two points from an object to another. This type of animation eliminates the necessity for any lines of code, thus significantly reducing time and workload. Similarly, we borrowed inspiration from existing collaboration processes to achieve a coherent workflow to share and retrieve content.

2.3.1 Collaborative AR Using Pull-Based Development Model

The pull-based model has been widely used for software development and has enabled developers to submit their contributions, typically as source code patches. After contributions have been submitted, they have to be evaluated prior to getting accepted and merged to the existing project. This review process, along with the support for multi-user collaboration, facilitates an attractive model for a classroom environment due to the beneficial presence of a moderator to filter wrong information. The idea is to make the student an active member in the learning process, including becoming a participant in the optimization of the learning content. All students can volunteer–and be rewarded for–their contributions to the class. As such, an active learner becomes a contributor to a network of fellow students and instructors, who are invested in working together towards a similar goal. There are four integral stages in our pull-based development process:

File Management

Unlike common open source projects, which typically include source code files, an AR project includes data files of different formats, such as mp4, jpg, obj, txt and etc. Thus, an effective file management strategy is needed to support the pull-based collaboration process. Drawing inspiration from the file management system in an operating system, we created a structured xml file to store the metadata of every file in the project. These metadata such as file index numbers, file types, creator ID, and many other file attributes, serve as the file handler which can help users keep track of files and perform further operations.

Online Repository Setup

In the context of software development, the online repository contains all the project files created by the moderator (i.e., instructor) and is accessible to the designated group (i.e., members of the class). The instructor pushes/uploads the AR project which was initially created, to the online repository on the cloud and then lets students clone/download it to their local machines for use in the class. The students' local version of the project can be subjected to future changes without affecting the instructor's initial project which is stored online.

Pull Requests

In a typical version control system, pull means downloading and merging the new data to the original project while pull request describes the process where a contributor requests a moderator to pull a contribution. After completing the AR project provided by the instructors, a student can make contributions to it by adding to the parts where he/she thinks more detailed explanations or information are needed. These modifications, which are in the form of text, image, video, or 3D drawing lines, are pushed/uploaded to the cloud for teacher's review. Meanwhile the student sends the pull request which essentially is requesting the teacher to accept his/her contributions.

Contribution Evaluation

Instructors need to verify that the contribution is correct and valuable. Only after the contribution is approved, it can be merged into the original project.

2.3.2 Interaction Modalities

While the traditional pull-based development model lowers the entry barrier for potential contributors (since a pull request can be made by anyone), it also increases the burden on integrators, who are responsible for evaluating the proposed changes and integrating them into the main development line [119]. It is particularly true for instructors who serve as the supervisors of the class since they have to both handle pull requests and help out students in need during class time. In order to alleviate the burden of instructors, we introduce an original type of pull-based model, *"local pull"*. Local pull combined with global pull, which is based on the traditional model, are the two types of interaction modalities facilitated by our platform.

Local Pull

Local pull requests are approved by students in need of help and sent by students who volunteer help. Students can help out others by adding explanatory components (e.g., images, video, text and etc.) to the project and sharing them by pull requests. Then, the struggling students can browse the suggestions provided by contributors and choose the most helpful ones to merge while these changes only take effect on their local device. This process, which happens during class without the instructor's involvement, encourages interactions among students while reducing their reliance on instructors.

Global Pull

Global pull requests are approved by the instructor and sent by students. Once the changes are merged, they will take effect globally(i.e, to all the class). Students are only allowed to make a global pull request after they finish the project and these requests are handled by the instructor after class. We implement the global pull to help instructors improve the tutorial which will benefit students from a future class given a new iteration of the learning content.

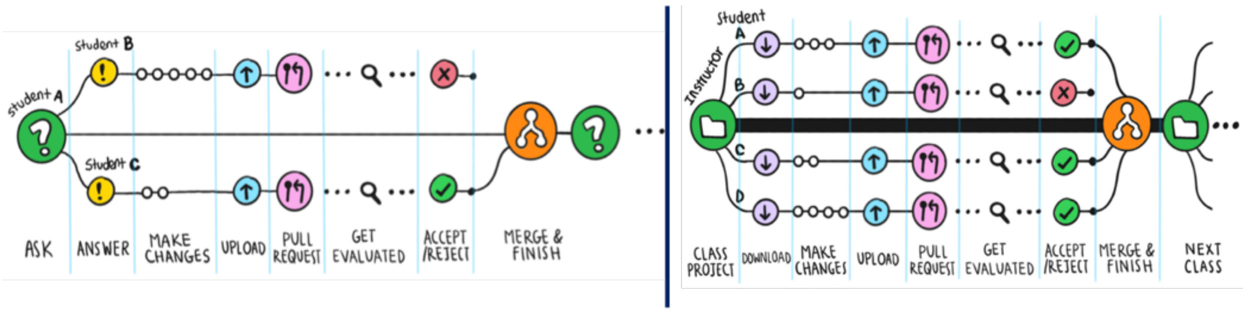

Figure 2.3. (Left) *Local pull*: Student to student collaboration workflow. (Right) *Global pull*: Workflow for instructors selecting contributions from students to improve their original AR project.

Figure 2.3 describes our vision for the customized pull-based collaborative development process. To simplify, we only include three students (*Student A, B, C*) for local pull while one instructor (*Instructor*) and four students (*Student A, B, C, D*) for global pull. However, it is applicable for as many instructors and students as needed.

2.4 Interface and Design Rationale

We designed our MetaAR application with specific design goals in consideration: *efficiency*, *accessibility*, and *reusability*. To accomplish these design goals, we needed extensive storyboarding and planning, to ensure that the users could be given all the tools necessary for the creation and access of AR learning content, as well as a coherent process to share and reuse content from contributors. *Efficiency* ensures that every process delivers the user's expectations while investing the least amount of time and effort. For example, if a user wants to create an animation of *object A* moving towards *object B*, rather than make the user trace

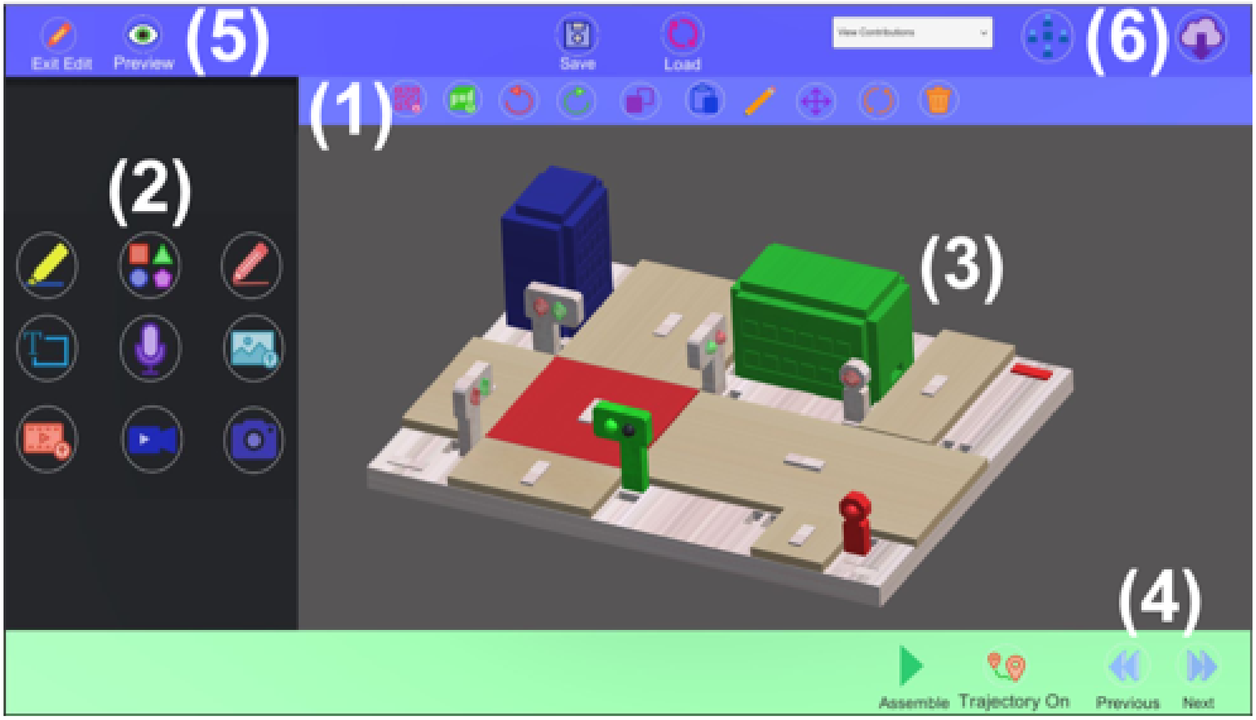

Figure 2.4. Main interface of the MetaAR (*Instructor Mode*): (1) Toolbar; (2) Animation Palette; (3) Canvas, (4) Controls, (5) Edit Mode, (6) Collaboration Panel.

the path, the system automatically generates the path, upon the selection of each object. *Accessibility* ensures that every feature of the system is cohesively and readily available. If the user requires to post a question or wants to create a specific type of content, then the Panel should easily guide them towards the request. *reusability* ensures that the AR project created by the instructor is reusable for future iterations of the class and to other instructors.

The main interface of the MetaAR consists of six components (Fig. 2.4). The Toolbar on top presents all the basic tools to manipulate the 3D models. The Animation Palette presents diverse options to provide object behavior, annotations, and tutorials to introduce into the scene. Only one animation option should be active per each step. The Canvas provides space to place the 2D/3D objects, create animations, and add annotations. The Controls allow the users to rewind, or forward the instructions. Edit Mode allows the users to enter the drag-and-drop animation interface to animate the scene. The Collaboration Panel enables the users to participate in the collaboration schemes previously mentioned.

Figure 2.5. Angle adjustment process: (1) *Object A* and path have the wrong orientation; (2) *Angle Adjustment* tools can be used; (3) *Object A* and path are aligned. Sample objects from our mini smart-city user study.

2.4.1 AR Environment Setup

Setup is a prerequisite for interaction with the virtual content within the physical world. This process is necessary to obtain the fiducial markers that are placed in the scene, bind them to a virtual object, or associate data to a position within the environment. The initial setup is enabled by the *Marker Tool* in the Toolbar, which provides access to QR codes. The Toolbar also allows to upload any objects using the *Object Tool* from the local device and to automatically assign each to a marker. Both tools enable distribution across the scene by pressing select + tap on the object or marker. To transform an object, users have to select + drag (*Drag Tool*) the object to a desired location. Then, to rotate, users have to select + rotate (*Rotate Tool*) the object to a desired angle. For precise angle adjustment, users can access the *Angle Adjustment* tools (Fig. 2.5). Objects can be duplicated (select + *Copy Tool* and tap + *Paste Tool*), and also deleted (*Delete Tool*). Actions within the virtual environment can be changed by using the *Undo Tool* and *Redo Tool*.

2.4.2 AR Spatial coordinates

Our system enables two different inputs to set the spatial coordinates upon which to overlay the augmentations: (a) QR code tracking, which overlays content directly on tracked

Figure 2.6. Creating Animation Process: (1) select start point from *Object A* and set; (2) select finish point from *Object B* and set; (3) path is generated and instructor can preview animation.

object; (b) ground detection, which provides no tracking of objects but sets reference coordinates for AR overlay, and reduces the burden of using multiple QR codes.

2.4.3 Creating Animations

MetaAR allows users to create object animations one at a time in the *Canvas*. Users can select the *Edit Mode* to start the animation (Fig. 2.6). To create a new path from one object moving towards a target object, select + *Set As Moving Object*. Once the target is identified, select + *Set As Target Object*. A path is automatically generated from the object to the target. The animation features include two types of manipulations: (1) transform an object, which allows the users to change the coordinates of the object in the scene, (2) pivot point selection, which allows the path to be generated from a specific point or line from the object towards a specific point or line from the target. The trajectory of the path can be visualized or hidden in the scene, and finally stored.

2.4.4 Authoring Visually-Oriented Microtasks

Visually-oriented microtasks are time sensitive short hints within an animation step that are designed to attract the attention of the user, and deliver visual information. For example, in an animation in which the part of the information is: *If breadboarding situation is to <place a voltage regulator in breadboard>, then <select the voltage regulator LM7805>*. Then, the options available by the *Animation Palette* are: (1) *Highlighter Tool*, which allows users to change the color of the selected object, (2) *Shapes Tool*, which enables users to place a bounding shape surrounding an object, (3) *Draw Tool*, which gives users the capability to draw a sign or figure on the object.

2.4.5 Authoring Knowledge-Oriented Microtasks

Knowledge-oriented microtasks are time sensitive hints to generate, and collect information from users' working memory. This type of information is typically abstract or conceptual, and requires a longer explanation to fit into the overall task. Within the animation, the microtask could be: *If breadboarding situation is to <create a voltage divider>, then <memorize that a voltage divider turns a large voltage into a smaller one by using two series resistors and an input voltage>*. The tools provided by the *Animation Palette* are: (1) *Annotation Tool*, which creates a textbox to deliver a message, (2) *Voice Tool*, which allows to record a voice message, (3) *Diagram Tool*, which allows the user to introduce a diagram or an image into the scene.

2.4.6 Authoring Spatially-Oriented Microtasks

Spatially-oriented microtasks provide just-in-time brief information to properly conduct an operation. For example, in an instruction in which the user needs to perform an action: *If breadboarding situation is to <connect the voltage regulator LM7805 to the microcontroller>, then <connect the output of the LM7805 to an available pin of the microcontroller>*. The suggested tools by the *Animation Palette* are: (1) *Take Picture Tool*, which enables the users to demonstrate an action by an image, (2) *Video Upload Tool*, which allows the users

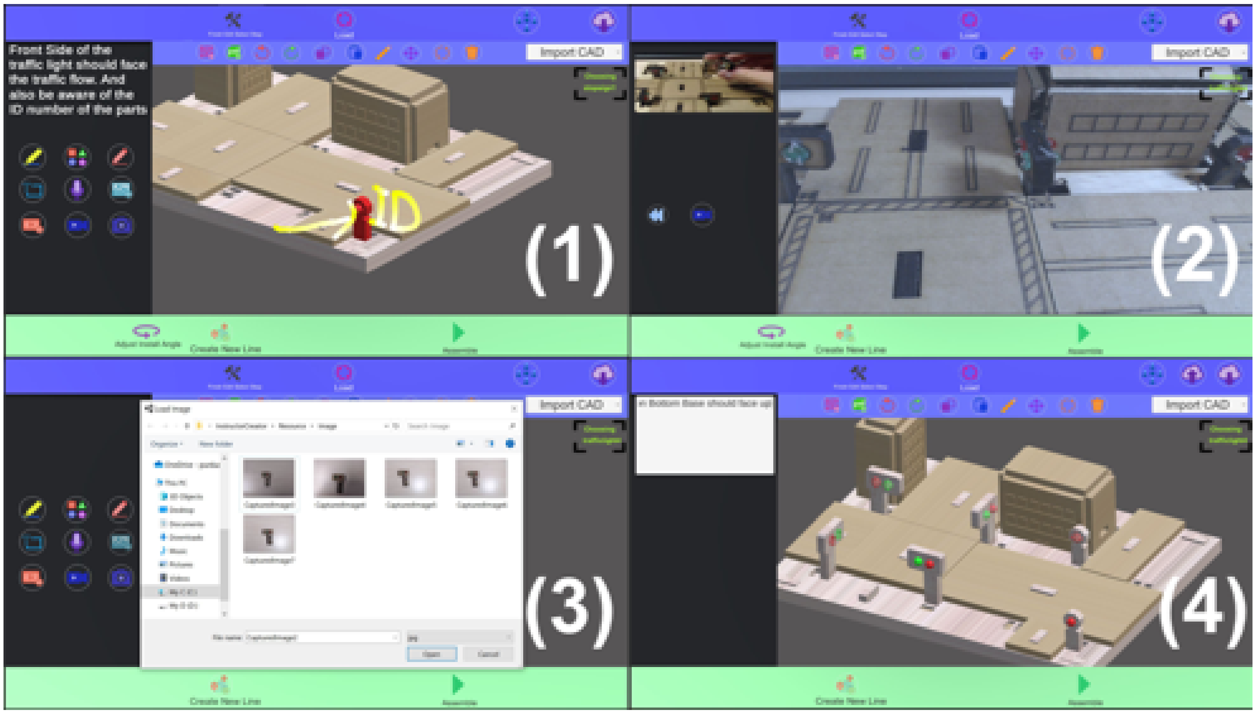

Figure 2.7. *Animation Palette* examples (from mini-smart city user study): (1) *Highlighter and Draw*; (2) *Take Video* (record); (3) *Diagram* (picture upload); (4) *Annotation* (text). 2D editor as seen from *Instructor Mode* Perspective.

to upload a video with brief instructions, (3) *Take Video Tool*, which gives users the capability to record a mini-tutorial or an example in real time. Since an animation has already been created for each step, these suggested tools may be redundant, and typically recommended for more complex spatial tasks.

2.4.7 Instructor Mode

The functionality of the Animation Palette is similar for our system in *Instructor Mode* (2D editor) and *Student Mode* (3D editor in the physical world) as seen in Figure 2.7. However, *Instructor Mode* provides instructors with more features to moderate the flow, and quality of the information. Initially, the instructors are in charge of creating the *Original Project*, which is made publicly available to encourage students to make their own contributions. As such, only instructors are given the capability to accept or reject these contributions.

2.4.8 Student Mode

Student Mode allows students to start on the application as the recipients of the content generated by the instructors (Fig. 2.8). Upon cloning the original content, students are given the capability to make modifications, but these contributions can only be accepted upon revision by the instructions. Unlike the *Animation Palette* from instructor mode, we only kept essential features: *Draw, Annotation, Take Video, and Take Picture*, to avoid too many confusing features (i.e., upload files from local machine) that are unnecessary in real-time collaboration.

2.5 Implementation

MetaAR was developed in Unity Game Engine version 2019.3.0a12. We installed our application in Samsung Galaxy Tab A running on Android OS. We built a cloud server to enable file sharing and communication among users. We encoded the metadata of AR project files into an XML file which was uploaded to the sever along with other AR project files in runtime. The server maintained another XML file to keep track of the interactions taking place.

2.6 Design user studies

2.6.1 Controlled User Studies

To create multimedia material for a class (e.g., powerpoint presentations, manuals), instructors initially have to research, review, and outline relevant content before they can proceed to create visualizations or tutorials tailored to the needs of their class. In this controlled user study, we focused on the usability of our system, to evaluate whether the instructors could easily understand and use the platform to compose AR applications. While scripted content may not exactly mimic the complete creation process of an educational AR application, choosing the content of the application enabled us to cover all the concepts and features in our platform. Similarly, we introduced the platform to the students to verify whether they can understand and utilize all the features made available by MetaAR. The

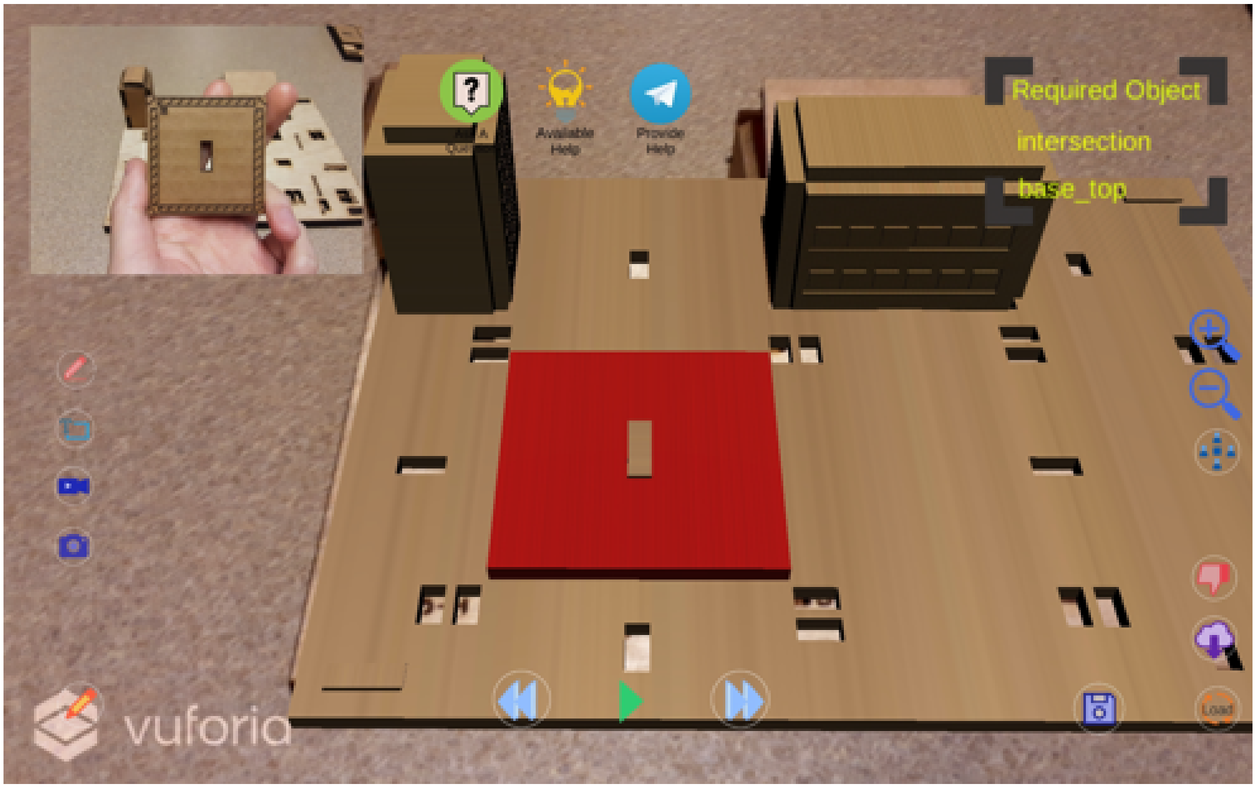

Figure 2.8. *Student Mode* Main UI.

ability to understand the features of our platform and create open-ended learning applications is a fundamental element of our MetaAR.

Setting and Participants

We recruited 12 participants (8 male, 4 female), and split them into two groups (instructors and students), based on background and experience. The 6 participants selected as instructors (M=24.4 years, SD= 1.63) were current or former teaching assistants with at least one year of teaching experience in STEM classes. We choose instructors from STEM classes for the following reasons: (a) accessibility, (b) electrical circuitry conveniently aligns to the spatial nature of augmented reality, and (c) we wanted to test the application by recreating the curriculum from undergraduate class we shadowed. The 6 participants selected as students (M=21.83 years, SD=2.41) who had completed a minimum of one semester of STEM education courses. The 12 participants' experiences using AR were as follows: mobile AR: 7 (58.3%); Microsoft Hololens: 5 (41.7%); tablet-based AR (33.3%). The participants' experiences using multimedia tools were as follows: video-editing tools: 8 (66.7%), video games: 3 (25%), powerpoint presentations: 12 (100%); VR (Oculus, HTC Vive, Google Daydream): 3 (25%).

Procedure

We gave each participant a Samsung tablet to complete the tutorial and tasks. The instructors (N=6) were given 'scripts' (exact procedural paper instructions) of the tasks they were supposed to follow, which were created directly from the first lesson (basic exercises) of the project-based electrical circuitry class we shadowed to inform our design specs. The students (N=6) had to complete the exercises following these instructions, randomly assigned, since all scripts were entirely similar. Each instructor and student received a tutorial lasting approximately 35 minutes on the features of our MetaAR. The participants learned about the main features of our application by following two brief animations between available primitives, which included modifying, customizing, and sharing content. The tutorial included a short walk-through about the capabilities of authoring and collaboration. Then, instructors were in charge of creating an application which included two tasks: (1) Introducing Basic Electronics and Concepts, and (2) Creating a Voltage Divider. The workflow of each task (i.e., an image-based script of the steps), was presented to the instructors, then they were requested to re-create them in AR using our platform. We carefully designed the content to ensure that all the features and functionality of AR authoring were tested. The students received the applications created for them by the instructors, and similarly had to perform a series of predefined modifications, that included all the features of the platform. We provided the context for each task as well as the files (.obj, .png) for the steps that required upload of local sources. Upon completion of the task, participants completed a questionnaire about their experience with MetaAR and sat down with a researcher for a semi-structured interview.

Results

Our 12 participants successfully completed Tasks 1 and 2 with minimal guidance. We presented the instructors and the students with a 5-point Likert scale (1-strongly agree, 5-strongly disagree) to rate their experience using MetaAR. The results we collected are the following: *I consider the tutorial session was sufficient to understand the system*, M=1.58, SD=0.86; *I think the authoring session was enjoyable*, M=2, SD=0.71; *I think the collaboration process was easy*, M=1.9, SD=0.7; *I think my overall experience was enjoyable*, M=2, SD=0.91. The participants were impressed by the ease and the flexibility of our platform: "*[MetaAR] is very easy to use because everything can be created in a matter of drag-and-drop. Even for a non-technical person like me, [MetaAR] allowed me to create timelines for my class. Now, [AR] becomes a new tool I can use in the classroom, especially to keep the students engaged with the material*" (P2). P3 reported a small learning curve, but proceeded to dismiss it: "*[MetaAR] does require basic training, but after becoming familiar with the buttons, gestures, which way things go, I think it was easier. Especially towards the end, when I definitely got the hang of it.*" From our controlled usability studies, our main takeaways were as follows: (a) avoid unnecessary features, which led to the simplified Student Mode we described in the framework section; (b) local-pull contributions should not require instructor's approval but direct student-to-student retrieval, otherwise the burden of selecting correct responses would remain on instructor's shoulders; (c) ground recognition is preferred to multiple QR codes unless individual object tracking is essential, because it provides the AR template with spatial coordinates and saves time for instructors from assigning QR codes to each physical object on the scene. We implemented these takeaways into our system.

2.6.2 Open-Ended User Studies

Setting and Participants

We wanted to investigate open-ended user studies to observe how our system would perform in a real classroom environment (Fig. 2.9). To that end, we recruited 40 undergraduate students (M=23.08 years, SD=2.44), 21 female and 19 male, without a STEM background

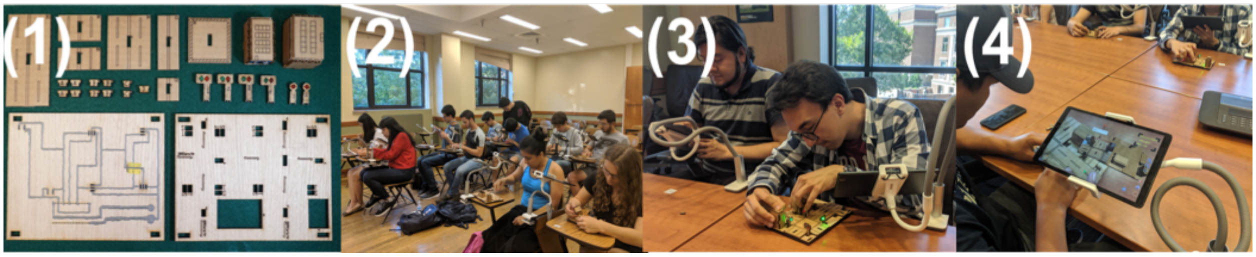

Figure 2.9. User studies overview: (1) components of the mini-smart city; (2) MetaAR implemented in class session; (3) student debugs the connections in his city; (4) student prepares to contribute using our software.

to participate in a class taught by one instructor from a design-and-tinkering class and an assistant instructor with 2 years of experience on electrical circuitry workshops for underserved youth. After a 30-minute tutorial on the features of the system, the instructors had freedom to design the virtual material for their class using our software. The principal instructor commended the system as *"easy-to-use"* and *"full of potential"*. For this class on IoT development, both choose to teach students how to construct a mini smart-city made out of cardboard material, conductive ink on plywood for the circuit connections, and electrical circuitry components (e.g., LEDs, battery, microcontroller). The objective of the class was to teach students about concepts such as polarity, connections in series and parallel, and current flow. The entire project was comprised of about 25 different steps/actions the users were expected to complete. However, regardless of the condition, they received instructions to 17 of them and were expected to explore and figure out the rest. The instructors designed all the material for the class, including the cardboard pieces for the smart-city, circuitry logic, and the step-by-step AR, explaining the assembly of major components of the task.

Procedure

Each class session lasted approximately two hours and the instructors taught in all sessions. We recorded all classes, and took notes and asked open-ended questions during the sessions to draw our observations. We divided the participants into four classes of ten students per session, each with a different condition: (1) No-AR: a typical class with two instructors; (2) AR-only: a class with AR content created with our software made up of the step-by-step assembly of major components of the smart-city; (3) AR-local: a class with AR content created by the instructors and contributions (e.g., help, hints, answers, suggestions) from student to student (i.e., local pull) using the AR software; (4) AR-local-global: improved AR content based on instructors' selected contributions from students (i.e., global pull) and the option of continuing contributions from student to student (i.e., local pull). For the No-AR condition, the main instructor taught in front of the class, while showing the instructions on assembling the smart-city by using a projector-view of his hands, along with his handling of the components, pausing for the class to catch up, and answering questions. This was the closest way to mimic a classroom and allow students a 3D perspective (e.g., different angles) of the components. After giving the basic instructions, both instructors approached students and helped with debugging.

Results

Table 2.1 shows the quantitative overall performance of the class per each condition. In order to understand whether an improvement in the AR content warranted less suggestions to the material, we broke down the average contributions of the students in the AR-local (M=2.2,SD=1.66) and the AR-local-global (M=1.7, SD=1.61) and performed a t-test between conditions. The number of contributions for AR-local were statistically significantly higher than for AR-local-global, t(9)=2.24, p=0.02. We also performed a one-way ANOVA to compare the four conditions, in terms of help requests. There was no statistically significant difference between the four conditions as determined by one-way ANOVA (F(3, 36) = 1.12, p = 0.36). As students worked on the smart-city, we evaluated errors by counting how many components or pieces were misplaced or wrongly oriented, each resulting in an "error". Thus, we analyzed the average number of errors for the four conditions. There was a statistically significant difference between groups as determined by one-way ANOVA (F(3,36)=12.37, p=0.00). A Tukey post hoc test revealed that the number of errors was statistically significantly higher for the no-AR condition (5.4$\pm$2.46, p=.001) compared to AR-only (1.9$\pm$0.94), AR-local (2.3 $\pm$ 1.1), and AR-local-global (1.6$\pm$0.91). We can observe that introducing AR into the classroom brings a sharp decline in overall error per class dur-

Table 2.1. Quantitative overall performance of the class per condition.

Total # \ Condition	No-AR	AR-only	AR-local	AR-local-global
Contributions	NA	NA	22	17
Help requests	8	5	10	11
Errors	54	19	23	16

ing problem-solving. Also, there was a large number of contributions for the AR-local and the AR-local-global conditions from students to their peers were requested and answered or volunteered.

2.7 Discussion of MetaAR Classroom Model

We consider our platform to be a support tool to teach and learn aspects of STEM subjects–while interacting with 3D virtual and physical objects–,different from the traditional pen-and-pencil methods. Following this new context, we organized our class model into *four categories* based on the observations we drew from our user studies, in which each student explored a learning-while-making approach: *Work* (i.e., building the smart-city), *Design* (i.e., creating the content), *Collaboration* (i.e., classroom dynamics), and *Technology* (i.e., using the platform). We evaluated how MetaAR is implemented in a classroom, more specifically how the pull-based model influences all four categories.

2.7.1 Work: Manipulating tangibles

We began the project by clarifying that all students were working towards a goal: every student had to successfully complete the city. Thus, students had to follow some instructions and also, figure out some steps on their own or with help from peers.

Facilitating Discoveries

Along the way, students realized some concepts underlying the task while assembling different pieces. For example, we observed how students would place the battery in the cardboard-based circuit board, then realize that it would not light up the circuit until they flipped the component. Thus, such exploration led to the interpretation of the concept of polarity (i.e., how current flows in one direction for some components). Research has shown that physical manipulatives (tangibles) can support STEM learning [120], [121]. In electrical circuitry, much of the phenomena taking place remains invisible, which can make the learning process difficult. In the no-AR condition this exploration was entirely a trial-and error process, in which these concepts were not always obvious, because other debugging issues in the circuit could be the cause of the circuit not lighting up (e.g., an error in the connections with the conductive ink). Similarly, in the AR-only condition, the instructors did not include AR effects to exemplify current flow; however, the assembly of major components was more straightforward due to the step-by-step instructions. Upon implementation of the pull-based model using the local and local-global conditions, some of the contributions included modifications that emphasized the importance of the direction of current flow (e.g., arrows, drawings) as suggested by the students, which simplified the acquisition of the concept of polarity. While these concepts could also be explained using other media, there is some evidence to suggest that AR provides better results in terms of learning as compared to other media [17], [18].

2.7.2 Design: Creating Learning Content

We observed that our AR system had multiple influences on how instructors created content. We also provided instructors with open mobility to choose how to structure their class and which tasks to choose; although we initially explained that AR technology was particularly salient in tasks that were sequential in nature (e.g., procedures) with phenomena superimposed.

Creating AR in AR

When designing a task for an AR environment, instructors typically need to consider that they are creating the learning content in a 2D environment but that it will be deployed in a 3D environment. The implementation of the pull-based model gave instructors and students a great advantage by enabling the creation of AR content (i.e., 3D models superimposed, 2D images, annotations, shapes, video, and any other technology embedded in a scene or an object) into an AR environment in real-time, pending approval from a moderator. This process of creating AR content in an AR environment enabled new interactions that provided instructors and students with not only spatial information (e.g., navigational cues in the form of annotations, letters to signal the correct orientation/position of an object), but also useful time-based information which related to the amount of time utilized to complete a step/action. For example, the instructors strategically left incomplete steps for the students to figure out. Using the pull-based model, students started contributing AR content on-the-fly and solving inconsistencies or gaps within the original project. This unique interaction made students highly participative as active agents in the learning process.

2.7.3 Collaboration: Between Students and the Class

Students answering questions made by peers

In the No-AR and the AR-only conditions, the burden of debugging each circuit fell almost entirely on the instructors. For example, several students would raise their hands with different concerns, and the instructors would try to assist them one by one, although sometimes this wait period fomented collaboration between the students and their classmates sitting next to them. This type of collaboration was not based on selection, but based on proximity. A common aspect across sessions was that students' first instinct was to refer to the instructors to solve their questions and if the instructor was unavailable, then they asked for help from fellow students, even after the collaborative technology was implemented.

Scalable Help

Once the collaborative model was implemented for the AR-local and AR-local-global conditions, we observed that students providing contributions (e.g., help, hints) were typically the most advanced in the assignment (∼30% of the class). This is different from collaboration conditions based solely on proximity, in that the software allowed for the best students to actively engage in helping the struggling students that were not sitting close to them. For example, contributors often recorded themselves troubleshooting a section of their circuits, took a picture of the orientation of a traffic light, sent an annotation with a recommendation on how to properly connect a component to the circuit board made of plywood. This type of selective collaboration made possible by our collaborative model aided the instructors: by relieving them of the pressure to help students one at a time and by directly providing help to the struggling students that was accurate and timely. The assistant instructor said that she had answered *"more interesting, more challenging questions in session 4 than session 3"*, referring to AR-local-global as the session with more challenging questions. Presumably, this means that as the global pull was implemented for this condition, the learning content was better navigated, thus giving more room for exploration and discovery of the many underlying concepts of the project. Another benefit is that a contribution from one student can be shared with several students as these move forward in the project. This means that help no longer needs to be one-on-one but can be distributed to different students as they access it as needed. One concern with scalability would be how to effectively answer help requests in larger classrooms, in which these requests can be duplicated. We foresee implementing a voting system in which students can upvote the questions they find the most relevant and in need of a prompt response.

Voluntary contributions

An observation from Table 1 is that the number of contributions was higher for both AR local and AR local-global conditions as compared to the number of help requests from students. We found this aspect particularly interesting because students were actively engaged and providing more help than was needed. In both sessions, we observed that students were exploring and stumbling into valuable discoveries, after which they proceeded to share new information with the class. Obviously, not everyone found it relevant at the time, but as students advanced in their projects and caught up, they made use of it.

2.7.4 Technology: Effective Learning and Problem Solving

Efficient debugging by tracing steps

In this category, we include our software and the electrical circuitry components, although the circuitry components are task-dependent and we will emphasize on how the AR technology influences the learning. In the No-AR condition, the only available technologies were the electrical circuits, which empowered students to manipulate components to test ideas or hypotheses (e.g., circuitry concepts). Efficient debugging can lead to learning about working circuits, but it was a slow, painstaking process. Also, exploration beyond this point was limited and dependent on discussion with the class, which was impeded due to instructors being busy helping struggling students. Once the local and local-global conditions were implemented, the debugging process became a collective experience, in which students were contributing with possible ideas on how to solve the circuit.

Iterations can improve the content

The AR-only condition was dependent on the material created by the instructors, which could not be altered since it was in read-only mode, thus exploration was limited to the information that the project provided (e.g., the orientation of small components was not evident, so the concept of current flow was not exemplified by the AR animations). In the AR-local pull, exploration of concepts was facilitated by students helping each other with the debugging process and suggestions to improve the AR content (e.g., added animations or annotations to improve a step, recordings showing how to assemble smaller pieces, arrows to emphasize direction and orientation of a component). The AR-local-global condition was the most student-friendly condition (i.e., the second iteration of the original AR project created by the instructor) mainly because the AR content considerably improved based on contributions made by the students from the AR-local session. Then, as students moved forward with the session, they continued using the technology to follow instructions and also to help each other debugging their circuits.

2.8 Limitations

We included 12 participants for our controlled user studies and 40 students (along with two instructors) for our open-ended user studies, but additional testing is necessary to validate the use of MetaAR across different subjects, classroom dynamics, and accommodations. A semester-long evaluation to analyze the effects and interactions (virtual and in-person) would also provide deeper insights into the role and features of the system, and how it adapts to diverse classrooms. Moreover, it will be interesting to evaluate how multiple iterations of an original project improve the quality of the learning content. We emphasize that MetaAR is a first generation prototype, which means that other features may be added/needed given the large range of classrooms and STEM subjects.

In terms of user scalability, we refer to the potential of a system to handle the growing number of users [122]. Currently, our system is designed to support up to hundreds of concurrent accesses which already exceeds the maximum size of a common class. In the future, if the need for accommodating of a larger class arises, the system can be scaled up by adding more computing resources [123].

2.9 Conclusion

We presented MetaAR, an authoring platform for collaborative AR. We demonstrated how we can leverage the medium of AR combined with cloud technologies to support selective (i.e., high quality) and timely collaboration, which enables a decrease in error during problem-solving. Apart from these novel interaction modalities, we observed how iterative improvement of the AR learning content (global pull) based on previous contributions made by students (local pull) can improve the original AR project and spark curiosity and creativity among students' learning process.

The next step will be to explore scaling the system to support a community of contributors with reusable templates of project-based AR learning content. The unique aspect of our technology for STEM learning is that it encourages discoveries of complex concepts through a trial-and-error exploration and facilitates effective debugging individually and collectively.

2.10 Acknowledgments

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2.11 Authors' contributions

AV conceptualized and designed the contents for this work; participated in acquisition, analysis, and interpretation of data. ZZ worked on architecture design and conceptualization; participated in acquisition of data. ZL designed contents for this work; worked on fabrication; worked on acquisition of data. KP has drafted the work, conceptualized it and substantively revised it. TR has drafted the work and substantively revised it. KR has drafted the work, conceptualized it, and substantively revised it. All authors read and approved the final manuscript.

3. ROBOTAR: AN AUGMENTED REALITY COMPATIBLE TELECONSULTING ROBOTICS TOOLKIT FOR AUGMENTED MAKERSPACE EXPERIENCES

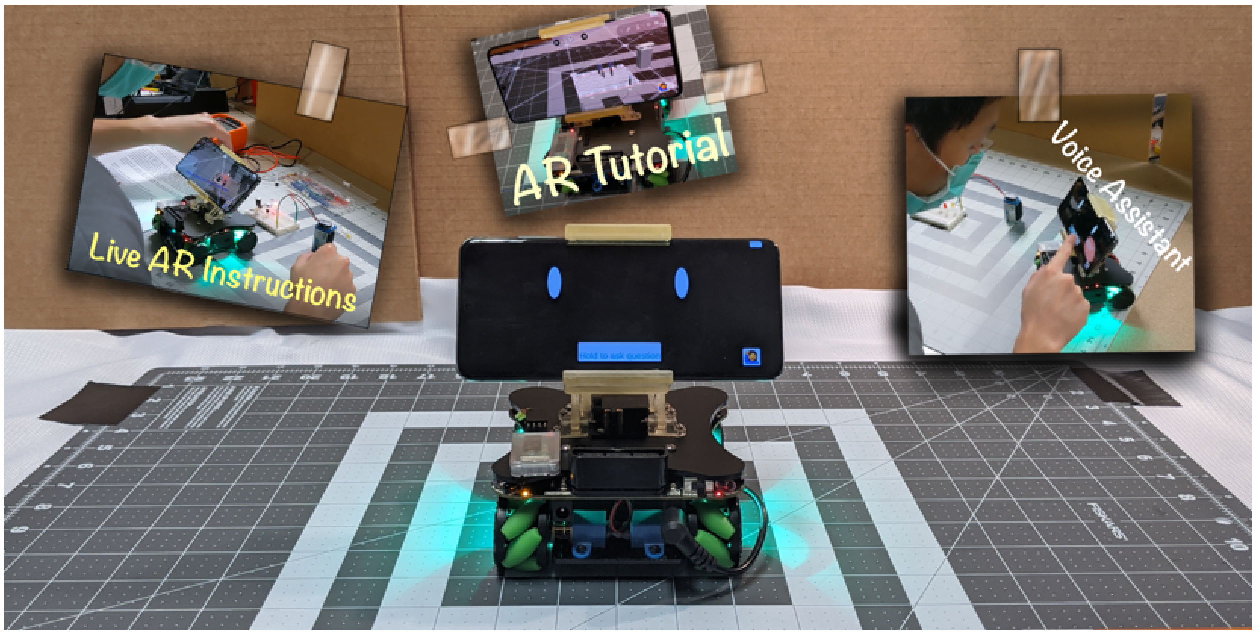


Figure 3.1. RobotAR is a versatile desktop robot which can make distance learning efficient and enjoyable. It can deliver online instructions, display AR tutorial, and provide voice assistance.

This chapter is presenting work published at the ACM CHI Conference on Human Factors in Computing Systems [124].

A robotic system cannot supplement the social in-person aspect of a classroom or the advantage of having an instructor standing next to a student and helping them with problem-solving. However, we can take advantage of new technologies, such as augmented reality (AR)–which overlays virtual information into the physical world [125]–to make use of the virtual world and superimpose instructions, hints, and visual cues into a student's workspace. AR also allows instructors to embody and immerse themselves onto the physical environment. In this paper, we refer to makerspaces with AR superimposed on them as augmented makerspaces. Thus, to address all the previous issues with distance learning at home, we design, prototype, and test RobotAR (Fig. 3.1), and provide the following contributions:

1. An approach for effective teleconsulting desktop-based robots in augmented makerspaces by enabling mobility and translational joints from the robot to better focus on areas of interest inside the workspace.

2. A toolkit for creating augmented makerspaces experiences using an AR-compatible robot that behaves as a tutor to the students, and as a versatile agent with access to the physical and the virtual world during teleconsultation.

3. A user study which compares current techniques for distance learning vs. an implementation of our toolkit.

Aside from our contributions, we will investigate into the effects of our system implementation into a distant makerspace environment. Our work is targeted towards undergraduate students who seek a makerspace-based instruction to mix creativity and technology learning. While we hypothesize that physical embodiment will result in an increase in student engagement [24]; more importantly, we raise another question: *Q1: To what extent does the use of RobotAR lead to an improvement in students' key competencies and user experiences.* If our robotic system allows learners to meet key competences, we ask another question from the point of view of the instructor: *Q2: To what extent does the use of RobotAR allow the instructor to offer more on-point instruction and at a higher level during problem-solving?.* Finally, if both questions result favorably, we wonder how an improvement in learning can influence in the interactions between instructors and students, in the form of the following question: *Q3: To what the extent does the use of RobotAR increase instructor's management and presence in the workspace and promote students' engagement and interest?.* Our work will explore all these research questions. This paper aims to advance our understanding of hands-on distance learning, which is becoming increasingly important in today's society.

3.1 Related Work

In this section we descrive teleconsulting tools and robots to benchmark our RobotAR platform. We discuss the practicality of current teleconferencing methods and explain how an embodied agent–a robot–is a more convenient,engaging, and helpful alternative for distance learning.

3.1.1 Social Robots for Education

Social robots are physical agents that interact with humans by following social roles and behaviors attached to those roles [126]. Social robots for education are intended for delivery of learning experiences through *social interactions* with the students. In this context, robots for education have been mainly used in three areas: (a) language acquisition and development, (b) science and mathematics education, and (c) technology and computer programming [127].

Past work has demonstrated the benefits of using a robot in the classroom. Perhaps the most common use of an educational robot has been robot tutoring [128], [129] for teaching a second language [130]. Robot tutoring for second language acquisition, has shown cognitive gains among children, through storytelling and adaption of the robot to the child's knowledge level [131]–[134].

Robotics for science and mathematics have included gaming using adaptive exercises [135] and teaching equations with the robot addressing an entire group of learners [136]. Technical education with robots typically uses the robot as the learning tool, instead of tutoring [137], [138]. These lesson plans involve introduction to programming the robot and hands-on activities that lead to tinkering and making the robot work [138]–[140]. Some of the most commonly used commercial robots adapted for educational interventions have been: NAO [141], RoboThespian [142], Bioloid [143], BAXTER [144], Darwin [145], TIRO [146], Keepon [147], LEGO Mindstorms NXT [148].

The robot as a tutor can provide learning support through multiple hints, visual cues, tutorials, and help with troubleshooting problems. In some cases, the robot is used as the medium to deliver the lesson to the class. Thus, the interactions between the robot and the students are limited and meant to capture the students' attention and encourage engagement with the subject [149]. The robot typically delivers the lesson from one to many students [150], [151]. However, the most frequently used tutoring robots for education allow to teach students individually, in which learning outcomes are highly dependent on the interactions between the robot and the student [152]. The problems with using robot as an individual tutor in the previously mentioned work, include the lack of scalability, portability, and cost. In our work, our toolkit provides a minimalist design that keeps the cost low and allows for easy installation. Similarly, the autonomous aspect of the robot will solve the scalability issue by allowing an individual experience with the robot, open to improvement.

3.1.2 Teleconsulting and Telepresence Robots

While social robots are used for physical interactions and communication, telepresence robots are embodied agents that enable the user to videoconference while on a moving platform from a distant location [126]. The user has remote control of the mobility and behavior of the robot, and communicates by using the robot as a delivery medium. Telepresence has been used to promote engagement and provide immersion to participants regardless of distance [153].

While the use of telepresence robots has been mainly used in the context of bringing distance students into a physical classroom, teleconsulting robots can be used to bring the instructor into the student's workspace [154]. New technologies (e.g., robotics, AR) can expand the consultation experience for students and make it easier for instructors to diagnose the problem. The benefits of using teleconsultation range from an increase in support and mentoring from the consultant to the consultee [155], an increase in access to rural youth [156], and an increase in frequency and quality of the interactions [157].

School-based teleconsultation has been successful in disruptive behavior consultation through videoconferencing. Further, teleconsultation was rated by the teachers as been just as an acceptable delivery medium as traditional face-to-face consultation [156], [158]. While teleconsultation has been an effective medium for instructors, studies have used them in static platforms (e.g., Kubi [159]) that do not mimic real-world interaction, in which students and teachers move frequently in their environment [154]. This is a significant limitation, because the quality of teleconsultation can be hindered if the consultant is unable to follow along and view the student's work. Thus, telepresence robots (e.g., [160], [161]) may be the best solution to the static nature of typical teleconsultation. In our work, we will be using a desktop-based teleconsulting robot to evaluate the quality of teaching in the context of an augmented makerspace.

3.1.3 AR for Robotics

AR technology, which is capable of creating immersive virtual interfaces, has been used for remote control and teleconsulting in human-robot interaction (HRI) research [40], [41]. Past research has explored AR interfaces in order to control the status and to plan robot activity [42]–[46]. These methods enable easy and intuitive manipulation of the robots [47], and facilitate debugging, operation, and mobility. Other AR interfaces in robotics have been used for object modeling and printing [48], education applications [49], [50], and adjustable wearable robots [51].

Additionally, spatial tasks and immersive visualizations enabled by AR are leveraged for telepresence in HRI applications [40]. For instance, AR can enable collaboration between distant users by providing them with the same virtual environment. Along these lines, users can visualize AR content superimposed with instructions or information of spatially-distributed tasks [22]. In this paper, we focus on AR information being delivered from the teleconsulting robot by the instructor. We investigate using a remote-controlled robot to provide the instructor's presence on the workspace combined with AR instructions for real-time help. The instructor is provided with a 2D interface to control the robot and create AR content (e.g., notes, drawings, diagrams). The student observes the instructions from the robot's head (i.e., the smartphone), which are superimposed onto the physical workspace.

3.1.4 Challenges of new technology in virtual makerspaces

In the past months, instructors were faced with a quick transitioning to online teaching. Currently, some of the most common platforms for virtual classrooms are Webex [162], Google Classroom [163], Skype [164], and Zoom [165], which is probably the most popular platform. This experimental transition has proven to be challenging, specially because this synchronous classes often lead to multi-tasking and distraction, and leave students feeling frustrated, fatigued, and complaining about “Zoom hangovers”, “Zoom bombing”, and "Zoom zombies" [166], [167].

In this new paradigm, the success of distance learning depends on the degree to which students find the agents of instruction (e.g., videoconferencing, teleconsultation) credible, are capable of learning from them, and find that their problems can be diagnosed with ease [126]. Credibility refers to the degree to which the students consider an instructor to be competent and an effective communicator [126]. Instructor credibility is important because it has great impact on the effectiveness of learning [168], [169]. In the past, credibility has focused on in-person studies of classrooms and while there is some evidence on the credibility of telepresence robots for education [126], questions arise on the effect of credibility when using teleconsulting robots, and virtual platforms and makerspaces.

Within the context of the work done in online makerspaces, we can discuss the current challenges faced by instructors. For example, when working with an Arduino board and electrical circuitry components, instructors had issues providing explanations given difficult camera angles and problematic camera zooming in on the small components [170]. While these issues can be bypassed by the instructor using multiple cameras at the station, on the students' end this remains a problem, specially when they require the instructor's help with diagnosing flaws with their circuits. Our teleconsulting robot, which has a top with two degrees of freedom, can tilt and zoom, thus overcoming the aforementioned problems encountered in virtual makerspaces. Also, our AR instructions will provide spatially distributed information, which will aid instructors in explaining clearly what the steps and connections look like when positioned in the physical world.

3.2 Requirements Elicitation

Since STEM distance learning in virtual makerspaces presents its unique set of challenges, we wanted to understand how an AR-compatible robotics toolkit would be an appropriate solution to this context. We interviewed 4 instructors and 10 students who had participated in previous full-day sessions of an online makerspace over an 3-day period, in which the participants took part in engineering activities and learned basic electrical circuits. Two of the instructors had more than 2 years of experience with physical makerspaces and workshops, and two had volunteered for their first virtual makerspace. Instructors were encouraged to reflect on their experiences by responding to the semi-structured interview. We conducted separate interviews with each instructor over a 1-hour period. Interviews with students were surveys completed voluntarily.

3.2.1 Findings

Students expressed appreciation and contentment for their instructors and their quick adaptation to the new format of distance learning. Overall, students and instructors showed a positive attitude towards virtual makerspaces; however, this enthusiasm was mostly related to the opportunity of realizing the activity at all, instead of getting cancelled, and of using technology in a meaningful way. Also, they recognized several issues with these new interactions and the way in which problems were solved among participants.

(R1) Need for teleconsultation for proximal demonstration. Students reported missing aspects of physical makerspaces. More specifically, they felt a lack of demos "on-the-fly". Face-to-face sessions meant that the instructor walks toward their workspace and sometimes, quickly shows a student a short example of something they did not understand or instructions from which they fell behind. This provided encouragement and support to continue working on the material. Similarly, instructors reported that the ability to diagnose a problem depended on them being able to approach students and analyze what was wrong with their work.

(R2) Need to reshape the landscape. An instructor pointed out that screens can be limiting and lack 3D perception of what the instructions look like. There was a consensus among instructors that they see the future of distance makerspaces to provide learners with a more immersive interface, such as mixed or virtual reality.

(R3) Need for reshaping the hardware. Instructors and students all reported issues with videoconferencing when instructors wanted to hold components or demos towards the camera, and when students needed to show their progress and request help with problem-solving. Our technology needs to solve the aforementioned issues in terms of facilitating zooming, centering, and adjusting the camera angles. More importantly, the hardware has to tilt, zoom, and move so that instructors and students can capture any area of interest within the workspace.

(R4) Need to relieve the instructor. Virtual learning can be difficult, specially when trying to diagnose problems and communicate instructions from a screen. Instructors reported that about half the time of the session was allotted for debugging and troubleshooting of students' errors. In order to alleviate the burden placed on instructors, we should have an initial helper in the form a AI voice assistant, which can provide hints to help solve issues with the work; thus, teleconsulting instructors takes place if students are not satisfied with the aid or if they would like check-ins.

(R5) Need for a scalable architecture. We need to support cloud capabilities to enable multiple students to simultaneously participate in an augmented makerspace. Students reported that much of the vibrancy of makerspaces is due to the community of makers to showcase and demo their work between makers of different skill levels.

3.3 System Overview

3.3.1 Hardware Platform

Base

The robot's base (11.5cm x 11.5cm x5cm) with its main components is shown in Figure 3.2 (Left). The onboard microprocessor ATmega328P controls the behavior of the robot by taking command signals from the Bluetooth module HC-06 and translate them into actuation signals driving the electric motors. The Mecanum wheels on the bottom are designed to move in any direction without turning the direction of the wheels. It is perfectly suited for constrained spaces such as students' desktops. The 6000mAh battery powers the robot to work for about 1.5 hours without recharging.

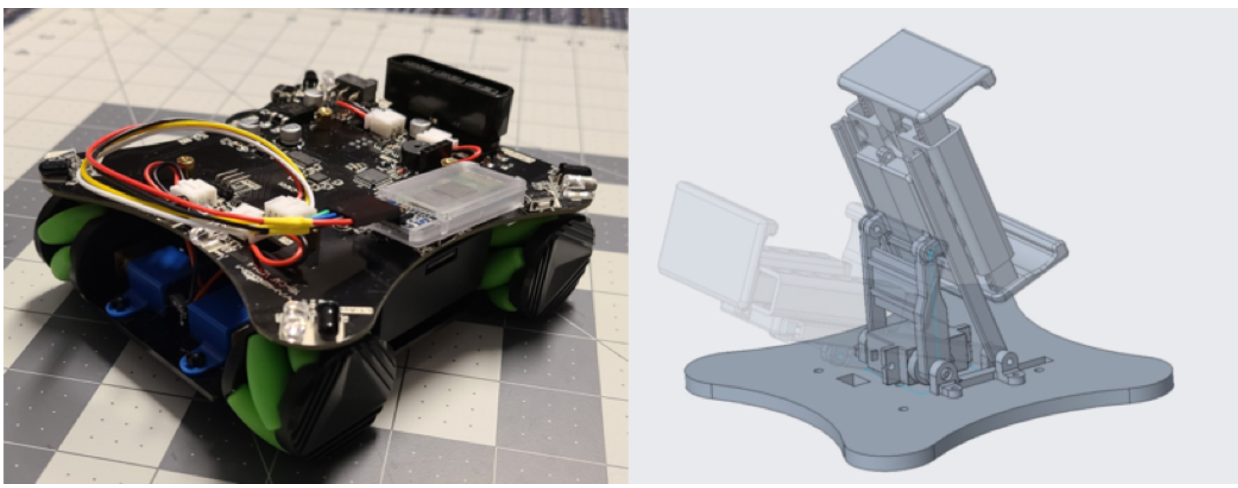


Figure 3.2. *Left*: Base of the robot. *Right*: Customized phone holder.

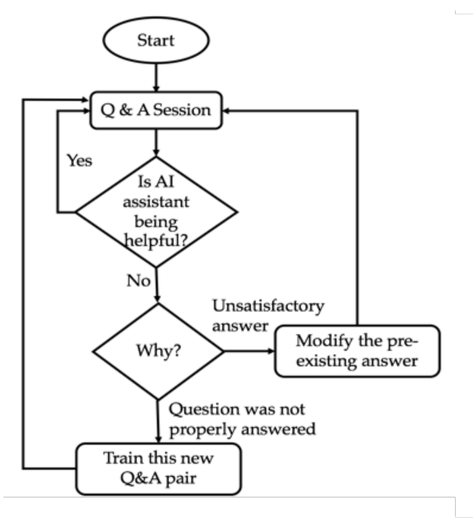
Customized Phone Holder

We designed and 3D printed an adjustable holder, as seen in Figure 3.2 (Right), to mount the phone on top. The remote-controlled servo motor attached can alter the holder's tilt angle from 25 to 70 degrees. It gives instructors the flexibility to change the viewing angle and to focus on areas of interest in real-time.

Smartphone

The smartphone is responsible for multiple tasks. It captures student's workspace with its rear camera and streams it to the instructor's side. Corresponding instructions are then subsequently forwarded to the phone. The commands to the robot are also routed through the phone before they reach the microprocessor. There is no special requirement for phones, as long as they are AR-compatible. A student can use his or her own phone to work by simply mounting it on the holder and pairing it with the Bluetooth module.

3.3.2 Software Implementation



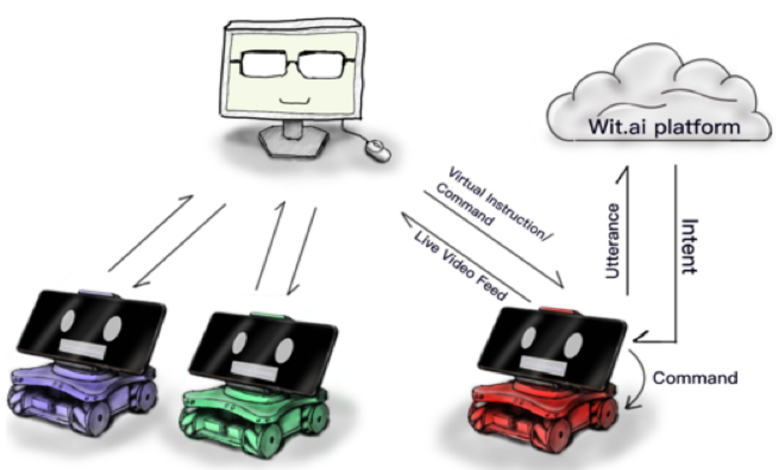


Figure 3.3. *Left*: Flow chart for iterative training process. *Right*: Network architecture.

AI Voice Assistant

Our elicitation requirements found that there is a need to relieve instructors from answering similar questions repeatedly throughout the session. To tackle this problem, we trained an AI voice assistant responsible for providing hints or direct answer–to a common set of questions we trained for the makerspace session–using the Wit.ai framework[171] which has advanced natural language processing capability. If the AI assistant understands the questions asked, it instantly displays pre-logged answers on the screen. To create a competent AI assistant, which can recognize questions comprehensively and provide the most accurate answer, a sufficient number of questions and answers are needed for training. We designed an iterative scheme to progressively train the assistant as seen in the schematic of Figure 3.3 (Left). Whenever a student finishes a Q&A session, he or she is prompted with a question asking if the AI assistant provided the appropriate answer. If not, the system automatically logs the question that was asked, for later reference by the instructor. An unsuccessful Q&A experience could be caused by two possible reasons: either the question is not properly recognized, or the answer is not satisfactory. In the first case, the instructor adds the new question-answer pair into the training queue. In the latter case, the instructor can choose to modify the preexisting answer should he or she deem it necessary. If this process happens periodically, the accuracy of the robot improves over time.

Network Architecture

RobotAR was developed in Unity 3D, which is a game engine. The network architecture we built to interconnect each unit of the system is shown in Figure 3.3 (Right). First, the phone transmits the live-video feed to the instructor's computer, and allows it to receive virtual instructions and robot commands. This bilateral connection is established with the TCP/IP protocol, which ensures transmission reliability. Eventually, command signals are routed to the robot using Bluetooth protocol. Bluetooth protocol is perfect for low-cost, low-power, and short-range transmission between electronic devices. Further, since the Wit.ai is a cloud-based framework, every student's utterance to the question is posted to a remote server for processing. Subsequently, the result which represents the corresponding intent, is sent back to the phone. Both utterances and intents are transmitted using the HTTP protocol.

Student's User Interface

The user interface for the robot consists of four scenes: *Setup*, *Standby*, *AR Animation*, and *Teleconsult* (see Figure 3.4).

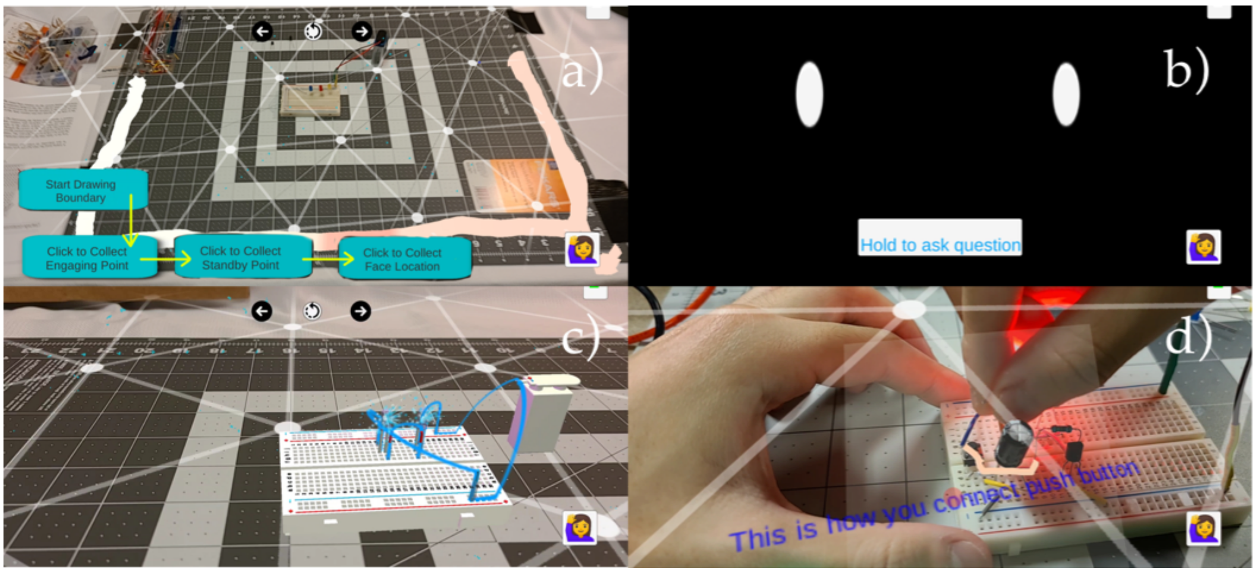


Figure 3.4. UI scenes on student's end. (a) *Setup*; (b) *Standby*; (c) *AR Animation*; (d) *Teleconsult*

Setup: Students first scan the table surface using their phones. This process is used to obtain the position of phone relative to the surface. It is a prerequisite for making the virtual content appear in real-world locations. Then, students draw a safety boundary, as an enclosed circle on the phone's screen, that represents the robot's available area for movement (i.e., workspace). Finally, students are required to designate "Standby Point", "Engaging Point", and "Face Location", respectively. Standby Point is the position in which the robot stays idle. Engaging Point is the initial position the robot moves to, as soon as teleconsult mode begins. Face Location is the position of the student's face. This information allows us to ensure the phone's screen always face the student, regardless of where the robot moves to. Drawing boundaries, determining facial position with respect to the 3D space, and defining spatial points are supported by the computer vision algorithms provided by ARCore development kit [172], in which the camera extracts feature points of the area to transfer 3D coordinates information to the system.

Standby: When the student is not in need of help, the robot moves itself aside while remaining in the field of view. If a problem occurs, the student can ask the AI voice assistant directly or enter the Teleconsult mode. In the first case, answers in texts and images are displayed in the current scene. In the second, it moves to Engaging Point.

AR Animation: We added several AR animations to introduce abstract concepts to students. These animations–which are initially displayed at the beginning of the session–can always be reviewed by students when scrolling back to this scene. Compared with traditional text-based or video-based tutorials, AR delivers a richer user experience and conveys spatial information which is important to hands-on tasks.

Teleconsult: Once the robot enters Teleconsult mode, it moves to the Engaging Point to assist the student. During this period, the robot behaves as an agent for the instructor. Thus, the robot can travel both manually and automatically. RobotAR starts from an initial position for teleconsulting. Its location is typically set at a point in which the camera can have a full view of the workspace. Then, the robot will automatically travel to this point and remain in place, until the instructor chooses to manually move the robot. Detailed information on how instructions are carried out will be discussed in the latter section.

Instructor's User Interface

The user interface for the instructor is designed for the computer platform. It consists of two scenes: *Connection* and *Instruction* (see Figure 3.5).

Connection: Each student's teleconsulting request is shown in this scene. Once it is accepted by the instructor, a one-on-one connection with the student is established. If a request is initiated when the instructor is unavailable, the student is notified and placed in queue.

Instruction: This scene can be separated into four regions. The live view window (see Figure 3.5a:Right) shows the student's real-time workspace. The command panel (see Figure

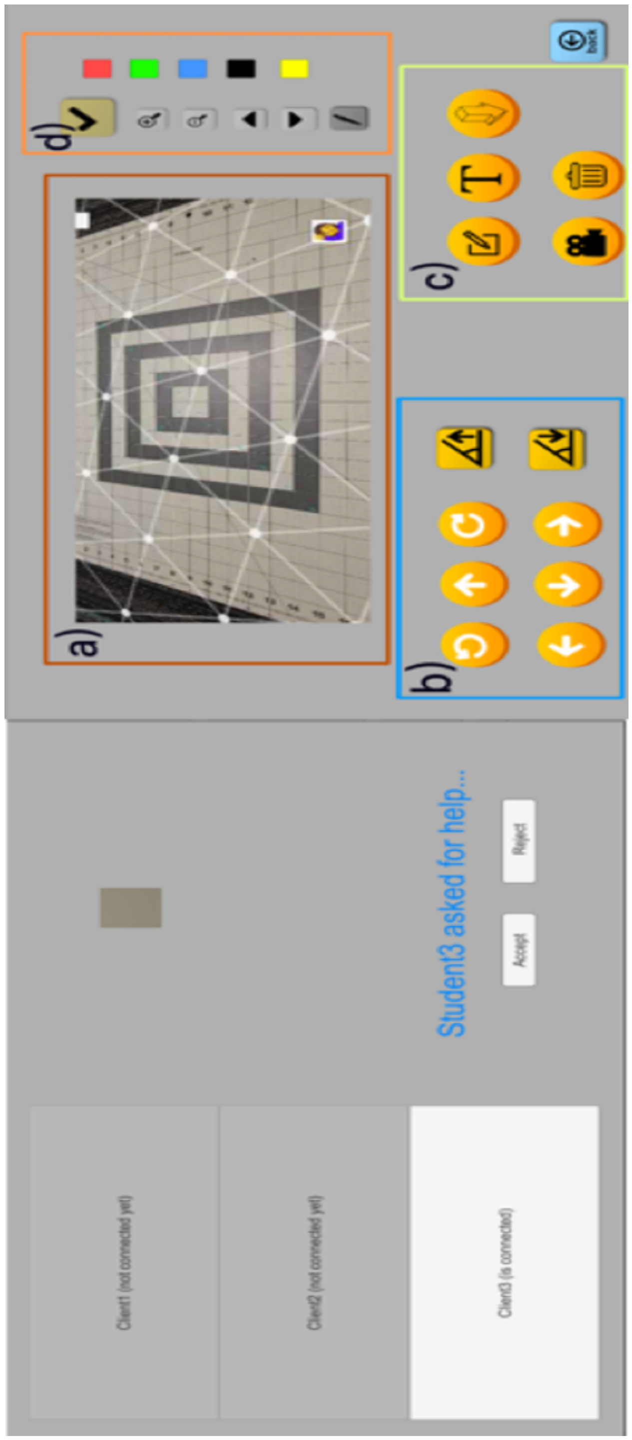


Figure 3.5. UI scenes on instructor's end. *Left: Connection. Right: Instruction.*

Figure 3.6. *Left*: Student A works on her circuits. *Middle*: Student B teleconsults with instructor. *Right*: Student C uses the voice assistance.

3.5b:Right) enables the instructor to operate the robot by moving it in any direction and tilting the angle of the phone holder. The content creation panel (see Figure 3.5c:Right) provides a variety of options for instructors to deliver real-time AR instructions. They can draw spatial lines, write text descriptions, add indicating arrows, and send out live-demos. Except for the live-demo which takes up the entire screen, other instructions will be superimposed on the student's screen as AR content. Instructors can further change the size, color, and positions of the instructions via the customization panel (see Figure 3.5d:Right). By default, students and the instructor are able to talk to each other throughout the process.

3.4 Evaluation

We performed a user study to test our setup and its effects on an augmented makerspace, involving a hands-on session between instructors and makers (Figure 3.6). In this user study, we mimic the methodology being used by instructors in virtual makerspaces and compare it to our robotics toolkit. Thus, we split our experiment into two conditions: (a) Video-conferencing with Zoom, (b) RobotAR, which includes AR delivered instructions, the voice assistant, and the option of teleconsulting. We decided to juxtapose our toolkit capabilities with the technology currently used and available in virtual makerspaces. Then, we will analyze how the effect of our toolkit for the instructors, the students, and the interactions between them.

3.4.1 Setup

First, the context of the class was a three-part single session–using RobotAR or Zoom, in which each participant was in a separate room. Each part lasted about an hour and there was a short break (5-10 mins) in between each hour. Likewise, the instructor was in another room, but given complete vision of the student's workspace via Zoom or our platform. There was at least one researcher physically present with each participant, while the participant teleconferenced with the instructor as necessary. Due to conflicting schedules and availability of robots, we had the instructor teach each session to 3 students at a time for both conditions. For the RobotAR condition, each student was provided with a robot; while for the Zoom condition, each student was provided with a tablet.

We chose a crash-course introductory lesson on basic electrical circuitry, which is part of an undergraduate class on electrical circuitry and programming. The series included the following parts: *Using basic tools*, *Connections in series and parallel*, *Transistors and capacitors*. We selected this use case due to the following reasons: (a) we had access to a robotics instructor, undergraduate curriculum for the class, and the students' kits from previous classes; (b) circuitry and tools are the most used subjects in makerspaces.

Thus, each session was split as follows: (1) Lecture part, in which students got introduced to the material, received some demos, and discussed the new concepts; (2) Hands-on making, in which students attempted to complete all activities on their own, and requested instructor's aid if necessary. The lecture part lasted about 30 minutes and the rest of the session lasted about two and a half hours. In the Zoom condition, following the lecture part which included some live-demos, students were able to teleconsult the instructor any time they required help. In the RobotAR condition, during the lecture part, students received the demos via AR. During the hands-on making, they were able to use the voice assistant first, then teleconsult with the instructor via the robot if they wanted help, clarification or a check-in.

3.4.2 Instruments and Activities

We gave each student with a Makeronics (7 in 1) electrical circuitry components kit, so they could participate in the experiment. These are the components from the kit which were used for the session: a breadboard, jumper wires, capacitors, LEDs, buttons, transistors, resistors. We also provided a multimeter for each student to take measurements of current and voltage, and verify connections. Since our audience had little knowledge in circuits, the activities at each of the three parts involved a short lecture on basic tools and components (e.g., LEDs, wires, batteries, multimeter) with instructor-guided circuits (e.g., 2 LEDs in series and 2 in parallel), and a self-guided follow-up circuit (e.g., combined series and parallel circuits, while writing down measurements of voltage and current).

3.4.3 Participants

We recruited 24 participants (15 male, 9 female) ranging from 20 to 28 years old (M=22.3, SD=2.65), all of which had experience with online classes and virtual laboratories, but little experience with electrical circuitry or virtual makerspaces. Participants were distributed in groups of 3 students per each session. The instructor leading all the sessions for both conditions had more than 2 years of experience teaching robotics classes and giving workshops at physical makerspaces. 15 of our participants had previous experience with voice assistants, 2 had prior experience with robotics, and 10 had experience with AR applications.

3.5 Results

3.5.1 Pre- and post-test evaluations

Since we are aware that electrical circuitry performance goes beyond whether the circuit is working or not, we decided to establish a coding scheme to evaluate conceptual knowledge and hands-on performance. Past work has shown that important circuitry concepts are pervasively misunderstood well into adulthood [173]; thus, we decided to test participants on these concepts in the pre- and post-assessment (after the 3-hour session) tests. Additionally, we tested on whether students were able to identify the appropriate schematic diagrams of the circuits they were building. For example, the participant may use redundant connections to complete a circuit. Similarly, students may be able to calculate and measure voltage and current, but may not understand them conceptually. Each answer was scored with a 0 if incorrect, +0.5 if answer had some substance, or a +1 point if correct. Then, the total points were normalized to fit into the 1-point scale for each category. Past work on circuitry has proposed similar coding schemes and categories to score circuitry learning [174], [175]. The categories we considered for evaluation were the following:

Knowledge of voltage and current conceptual and applied understanding of voltage and current; *Polarized component orientation:* the positive terminal (+) of polarized components are consistently oriented toward the positive terminal or pin(s) of other components; *Connections in series and parallel:* successfully connect one component to another in series or parallel, as well as knowing its effects on voltage and current; *Knowledge of circuitry components:* functionality , placing, and connecting LEDs, resistors, push buttons, capacitors, transistors, batteries; The next key competencies did not have a pre-test because they included calculations from hands-on performance. *Use of breadboard:* appropriate placing of components to power and ground rails and in respective rows; *Use of multimeter and measurements:* measuring resistance, voltage, current, conducting short tests; *Working circuit:* using appropriate components, wires, and making sure the circuit is closed.

4 Key competencies were analyzed by coding pre- and post-tests, graded on a 1-point scale. While 3 other key competencies were obtained by collecting the answers from lab manual (test). All tests were coded by one primary coder. Inter-rater reliability on both the pre-test, test, and post-test was validated by having a secondary person score over 25% of the data. From our rubric, two researchers in charge of grading had a Cohen's Kappa of 0.714. As for the workshop, we had to wrap it up at the 3-hour mark. From the Zoom condition, only 3 out of the 12 students managed to complete all the exercises available. While, 7 out of the 12 students managed to complete them from the RobotAR condition. The rest of the students oscillated between 25% to 75% completion of the exercises. As for the results of the pre-test, test, and post-tests by condition, these are summarized in Table 1.

We analyzed scores with our aforementioned rubric for the key competences assessment. We began with a Shapiro-Wilk normality test to verify whether the normal distribution assumption was not met. Thus, to analyze the significance of our results from RobotAR and Zoom conditions, we conducted the Friedman Test with a post hoc analysis from Wilcoxon signed-rank test. When comparing these conditions, the Wilcoxon sign-rank test showed a statistically significant improvement for RobotAR condition in 3 out of 4 conditions: *knowledge of voltage and current* [Z=-2.333, p<0.05, p=0.02]; *connections in series and parallel* [Z=-2.084, p<0.05, p=0.037]; *knowledge of circuitry components* [Z=-2.12, p<0.05, p=0.034]. Likewise, the learning gains between pre-, post-tests are presented in Table 3.1.

For the remaining key competencies, which are the scores obtained from the lab manual students returned, we also performed the Wilcoxon signed-rank test and found for that RobotAR condition showed a statistically significant improvement in all 3 competencies: *use of breadboard* [Z=-2.771, p<0.05, p=0.006]; *use of multimeter and measurements* [Z=-2.998, p<0.05, p=0.003]; *working circuit* [Z=-2.053, p<0.05, p=0.04].

3.5.2 Usability Evaluation

After the 3-hour user study session, we provided participants with a 5-point Likert scale (1-strongly disagree, 5-strongly agree) questionnaire. This survey was meant to assess the usability of RobotAR vs. the traditional teleconferencing media, Zoom. Figure 3.7 shows the average scores reported by participants. These results were representative of the following categories: *Engagement*; *Performance satisfaction*; *Voice and visual aid* from the system; *Instructor presence*; *Useful aid* from the instructor in real-time; *Teleconsulting experience*; *Interest* in the subject; *Awareness* of instructor; *Management* by instructor; *Frustration* with problem-solving; *Difficulty* of the learning material.

We conducted a Mann-Whitney U test on each of the categories. Thus, from the reported responses, we found participants preferred usability of RobotAR condition for the following (p<0.05): RobotAR (M=4.25, SD=0.829) provided a higher quality of voice and visual aid with its system than Zoom videoconferencing (M=3.167, SD=0.687), U=110, p=0.007; RobotAR (M=4.417, SD=0.344) improved the overall instructor presence as compared to

Table 3.1. Pre-test, test, and post-test results of key competencies assessment.

		Zoom		RobotAR		
Key Competency	**Time**	**M**	**SD**	**M**	**SD**	**Sig.**
Knowledge of voltage and current	Pre-test	0.246	0.263	0.254	0.235	$Z = -2.333$ $p < 0.05$
	Post-test	0.842	0.07	0.813	0.092	
	Gain	**0.790**		**0.749**		
Polarized components orientation	Pre-test	0.153	0.246	0.169	0.262	$Z = -1.095$ $p > 0.05$
	Post-test	0.813	0.084	0.788	0.068	
	Gain	**0.779**		**0.745**		
Connections in series and parallel	Pre-test	0.138	0.123	0.163	0.136	$Z = -2.084$ $p < 0.05$
	Post-test	0.596	0.214	0.763	0.146	
	Gain	**0.531**		**0.717**		
Knowledge of circuitry and components	Pre-test	0.167	0.155	0.191	0.166	$Z = -2.12$ $p < 0.05$
	Post-test	0.525	0.221	0.767	0.259	
	Gain	**0.430**		**0.712**		
Use of Breadboard	Test	**0.646**	0.155	**0.804**	0.144	$Z = -2.771$ $p < 0.05$
Use of multimeter and measurements	Test	**0.508**	0.155	**0.717**	0.228	$Z = -2.998$ $p < 0.05$
Working circuit	Test	**0.479**	0.13	**0.697**	0.21	$Z = -2.053$ $p < 0.05$

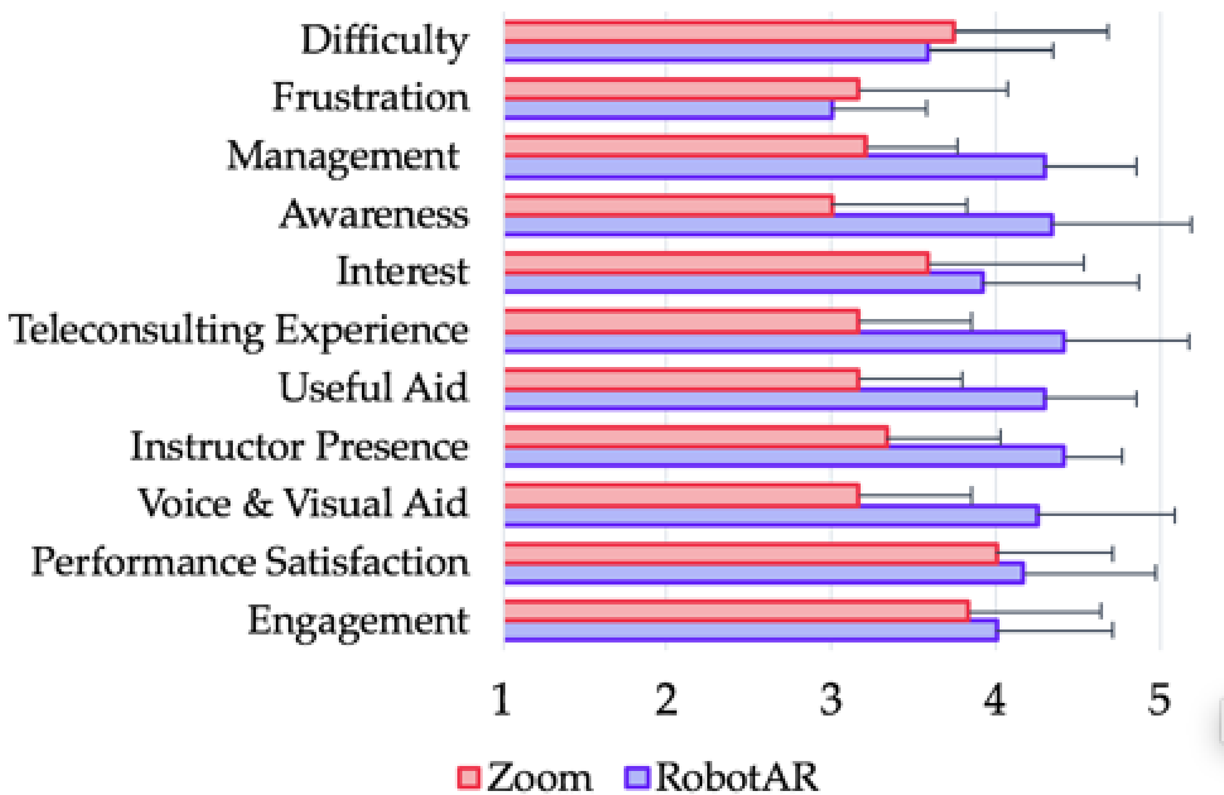


Figure 3.7. Results from average scores on the usability of RobotAR vs. Zoom. Purple: RobotAR, Red: Zoom videoconferencing. We used 5-point Likert scale (1-strongly disagree, 5-strongly agree. (*) : $p<0.05$).

Zoom videoconferencing (M=3.333, SD=0.687), U=131, p=0.000; RobotAR (M=4.292, SD=0.557) allowed the instructor to provide more useful aid in real-time than Zoom videoconferencing (M=3.167, SD=0.624), U=128, p=0.001; RobotAR (M=4.417, SD=0.759) provided a higher quality of teleconsulting experience than Zoom videoconferencing (M=3.167, SD=0.687), U=135, p=0.000; RobotAR (M=4.333, SD=0.849) provided greater awareness of instructor than Zoom videoconferencing (M=3, SD=0.816), U=126, p=0.001; RobotAR (M=4.292, SD=0.557) instructor's management of student's workspace than Zoom videoconferencing (M=3.208, SD=0.557), U=130, p=0.000. For the remaining categories no statistically significant differences were found (p>0.05): Engagement (RobotAR: M=4, SD=0.707; Zoom: M=3.833, SD=0.799, U=0.78, p=0.727); Performance satisfaction (RobotAR: M=4.177, SD=0.799; Zoom: M=4, SD=0.707, U=81, p=0.6); Interest (RobotAR: M=3.917, SD=0.954; Zoom: M=3.583, SD=0.954, U=83, p=0.505); Frustration (RobotAR: M=3, SD=0.577; Zoom: M=3.177, SD=0.897, U=66, p=0.727); Difficulty (RobotAR: M=3.583, SD=0.759; Zoom: M=3.75, SD=0.924, U=61, p=0.506).

3.6 Discussion

In this section, we discuss the findings of our user study and reflect on how they influence the questions we posed in the introduction.

Q1: To what extent does the use of RobotAR lead to an improvement in students' key competencies and user experiences compared to traditional teleconferencing platforms?

Students were overwhelmingly positive about RobotAR. There was a consensus among students that our robotics toolkit was a viable alternative to provide high-quality teleconsulting in an immersive, focused approach.

"It's fun, it's convenient, it's educative. I feel like I'm in a new age of learning."-P8

Our results showed that RobotAR was conducive to an improvement in assessment of key competences when compared to Zoom teleconferencing for 6 out of 7 categories: *knowledge in voltage and current, connections in series and parallel, knowledge of circuitry and components, use of breadboard, use of multimeter and measurements, working circuit.* Much of the learning that takes place at makerspaces is hands-on and through an exploration process. One common mistake among participants included which points in a working circuit were appropriate for measuring voltage or current. For example, if participants could not map the schematic of the circuit, it typically translated into a lack of knowledge on what it meant to measure voltage across the power source or across an LED. In our case, RobotAR provided students with important tools that accelerated or guided them through the discovery of these questions.

AR content. The AR animations that had been set up on the robot for the session were used in ways we were not expecting. Those animations were meant to be used as the lecture section to provide follow-along, basic information of circuitry; however, we found out that students were using those animations throughout the workshop to internalize or refresh some of the concepts they had not understood.

"In real life you can't re-play the TA."-P10, who reportedly used the AR to differentiate between capacitors and transistors and how to connect them.

There is a discussion to be had as to how much of the learning gains depend on AR, and why it should be used instead of a different technology (e.g., a video which loads on a website). In our setup, the use of AR was presented in two formats: (1) to provide tutorials for the lecture with demos for students; (2) to provide students with real-time notes/drawings from the instructor. (2) was a feature of our toolkit, enabled by the instructors' UI. This was especially useful, since access to the phone's camera and the toolkit, established the 3D coordinate system of the workspace. With (2), AR superimposes content and provides spatial information corresponding to students' specific workspace and requires no extra steps from instructors. Conversely, (1) is an optional process, since we decided to deliver the laboratory with entirely AR-based content. AR content is supported by the toolkit, but needs to be created in Unity 3D, which makerspace instructors can choose to do. However, students emphasized on the usefulness of being able to replay the content, rather than the format (i.e., AR, video), even if they found voice and visual aid to be helpful. Thus, we would recommend makerspace instructors to focus on creating tutorial content to the best of their abilities, whether in AR or typical video.

Voice Assistant. In most cases, the voice assistant was the go-to tool for participants who had a simple, quick question. For example, *"which leg is my positive side in my LED?"*; *"how do I read a resistor?"*; *"what is voltage?"*. Referred to as a *"first-responder"* (P2), students pointed out that the voice assistant helped them not get too complacent, just get a quick fix, but continue trying to solve their circuits by themselves. Similarly, students reported that it took away the anxiety of asking the "wrong question" or overwhelming the instructor.

"At first I use [the voice AI] because I don't want to rely too much on the TA...because I want to learn, so maybe I want help but not too much."–P7

"The AI helped me to not overload the TA with embarrassing questions. Simple things, [the voice AI] helps you fix."–P1

The effectiveness of the voice assistant is an ongoing process. As the database incorporates more utterances, it will become more accurate at responding to students' questions. Although incorporating more questions and answers into the database is a simple procedure, instructors–who are already in charge of all content creation–may consider whether this is a necessary burden. First, the size of the makerspace is an important detail upon which to take decisions. For example, if a makerspace has 5 instructors and 7 students, then maybe a voice AI assistant to answer questions may not be worth the effort. However, if that same makerspace has 5 instructors and 75 students, then the quantity and quality of available aid will be crucial for a positive learning experience. It should be up to instructors' judgement to decide whether a makerspace requires of the AI voice assistant feature.

Another important feature of makerspaces is brainstorming projects and solutions. This process is synergistic in a physical makerspace, because students are in close proximity, but in a virtual makerspace this is more constrained. One possible solution is for instructors to use a platform (e.g., Slack, Discord) in which students can share, brainstorm, and comment on each others' work. If so, this should take place before or after makerspace hours instead of during, so as to not distract students while they work on their projects. However, we consider the voice assistant for RobotAR–which was used during makerspace hours–to be a proxy for these brainstorming in-person sessions. After all, the AI is crowdsourced from previous sessions with students, and while it does not replace human-to-human interaction or brainstorming, it can become a placeholder to keep students engaged and feel like they are getting community support.

Instructor Teleconsulting. As for the teleconsulting, which was the favorite feature of the robot, students found the AR visual cues provided by the instructor (i.e., arrows, drawings) to be useful and engaging.

"I liked that you can contact the instructor, which is super convenient, because they can show you [the correct answer] in your scene and it's like you never left the lab."–P5

"For me, the instructor [teleconsulting] with the AR is best...it helps to accurately locate something into my view. With [the AR] there is no gap, I don't have to map from his view to my end."–P9

To provide context, the AR demos and the voice assistant were the first-stop tools of most participants. However, there was consensus among students that the teleconsulting feature–either by having the instructor make AR annotations in the students' scenes or by sharing his own camera to do a focused live-demo–was important to understand some difficult concepts that would otherwise make them fall behind. RobotAR, as an intermediary agent for teleconsulting, deviates from current makerspace practices (e.g., Zoom sessions), which require students to double as camera-men (e.g., zooming in, focusing) and creators (i.e., working on their circuits). These dual responsibilities–even with only basic phone functions–were too overwhelming and cumbersome for students. Without the robot, students had to change the position and focus of the camera, which kept their hands busy and unable to follow instructions from the teacher in order to receive timely help. Thus, while they worked on solving their problem, the tablets/phones ended up getting dropped and laying down on the table in disuse.

In terms of the documentation that instructors would typically require from their makerspaces, the lack of physicality would severely hinder instructors' ability to keep track of students' progress. In a physical makerspace, instructors walk around the classroom, glance over students' shoulders, and check progress status. However, in a virtual makerspace, these routine check-ups are difficult without interfering with students' concentration, by asking them to stop and cooperate with focusing/zooming into their workspace. RobotAR removes the need for extra work because the camera repositions according to the students' view or follows along. This is a promising step towards a pathway to have more natural interactions with distance technology, which should be the goal of all makerspaces. Also, this greatly reduces the workload of the students.

Q2: To what extent does the use of RobotAR allow the instructor to offer more on-point instruction and at a higher level during problem-solving?

"It's not just the movement of the robot, it's the voice!"–P4, who emphasized that while he liked how the robot could focus on his workspace, it was the instructor's voice–which could be heard as the robot moved along–which made him feel like the instructor was there next to him.

Several students pointed out that the combination of AR annotation plus voice from the instructor made the class content *"more interesting"* (P10).

The robot mobility and focus capabilities facilitated a higher quality of teleconsulting. Instructor had better access to students' problems, could provide visual cues and notes, and no longer had *"to worry about guiding the student to a particular area, I can use [RobotAR] to focus on what I know I'm looking for."* (Instructor). In this case, the instructor is referring to providing trouble-shooting help. The instructor reported that, for the RobotAR session, questions were not necessarily about problem-solving, but rather to ask for a check-up, more along the lines of: *"Am I doing things correctly?"*–P12. The instructor, who had previously referred to the Zoom session as *"chaotic-fun"*, expressed satisfaction at finding that students were somewhat better prepared in RobotAR condition. While this perceived increase in understanding was probably due to the other tools available (i.e., AR demos, voice AI), the instructor reported that *"it's always easier to help when [the students] get what they're doing"*. With all this in mind, the instructor was enthusiastic about the prospect of using RobotAR in future workshops.

Q3: To what the extent does the use of RobotAR increase instructor's management and presence in the workspace and promote students' engagement and interest?

As reported in the results, there was no statistically significant difference in engagement and interest between conditions. However, mean scores for RobotAR and Zoom were already fairly high to begin with. While we cannot claim that RobotAR provided an improvement in interest or engagement as opposed to Zoom, it did provide a significant improvement in user experience for several categories: *voice and visual aid from the system, instructor presence, useful aid from instructor, quality of teleconsulting, awareness of instructor, management of workspace.*

As we previously mentioned, the robot added to the teleconsulting experience, helped boost awareness and credibility of instructor and made students feel as if the instructor was next to them. P3 remarked that as *"the instructor was controlling the robot, I felt [the instructor] was here, more like his hands were in my [workspace]."*

It follows that if higher level problem-solving takes place over teleconsulting, then the instructor becomes more credible and the students are more satisfied with the level of workspace management and aid. For example, at different points throughout the experiment, students wanted to get assistance, but the instructor was sometimes busy helping out another student. If at this point, students–seeking assistance–had exhausted the resources (i.e., AR, voice AI), then they either continued problem-solving on their own or became distracted. Since our voice AI was still limited, then the available support was limited. We logged all students' utterances that were mistakenly classified or not recognized. In the future, our voice AI should continue to recognize a larger set of questions from students. Thus, while we had an engaged set of participants, we need to make sure to always have available resources to keep them concentrated in the work and not lose focus.

3.7 Limitations

While our network supports multiple users being part of the session at the same time; thus, problem-solving through teleconsulting is done in a one-on-one basis. This is due to the need for plane mapping so that the AR can be superimposed on the scene. For more efficient problem-solving, in the future, we will add a broadcasting option that will allow simultaneous teleconsulting for multiple people.

Also, our system only uses one of the phone's cameras during the whole process. Most current smartphones have multiple rear-cameras and switching between them will enable further view of the student's workspace to the instructor's benefit.

Currently, our robot does not have automatic object avoidance capability and relies on the instructor's navigation skill. In the future, we will add all the aforementioned functionalities to our toolkit.

3.8 Conclusion

In this paper, we presented RobotAR, a teleconsulting robotics toolkit to provide learning experience in augmented makerspaces. We introduce an AR-compatible, desktop-based robot that behaves as a tutor to the students, and as a versatile agent with access to the physical and virtual world. We performed a user study with 24 participants split into two conditions: RobotAR, a full implementation of the capabilities of our toolkit, and Zoom videoconferencing. The study involved completing a circuitry session to learn basic electrical circuitry. Our results demonstrated an improvement in several key competencies and an improvement in the teleconsulting experience provided by RobotAR condition. Also, we demonstrated that the instructor can facilitate a higher level instruction during problem-solving. Similarly, our toolkit provides an improvement in instructor's management and presence in the workspace. In this work, we advance our understanding of distance education, by removing the boundaries to high-quality hands-on learning, which is becoming increasingly important in our current society.

3.9 Acknowledgments

We wish to give a special thanks to the reviewers for their invaluable feedback. This work is partially supported by NSF under the grants FW-HTF 1839971, OIA 1937036, and CRI 1729486. We also acknowledge the Feddersen Chair Funds. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agency. We would also like to thank Kaiwen Li and Feiyang Wang for their feedback and help with this project.

3.10 Authors' contributions

AV conceptualized and designed the contents for this work; participated in acquisition, analysis, and interpretation of data. ZZ worked on architecture design; participated in acquisition of data. ZL designed contents for this work; worked on fabrication; worked on acquisition of data. XD worked on architecture design; JH has drafted the work and substantively revised it. KP has drafted the work, conceptualized it and substantively revised it. KR has drafted the work and substantively revised it. All authors read and approved the final manuscript.

4. COLABAR: A TOOLKIT FOR REMOTE COLLABORATION IN TANGIBLE AUGMENTED REALITY LABORATORIES

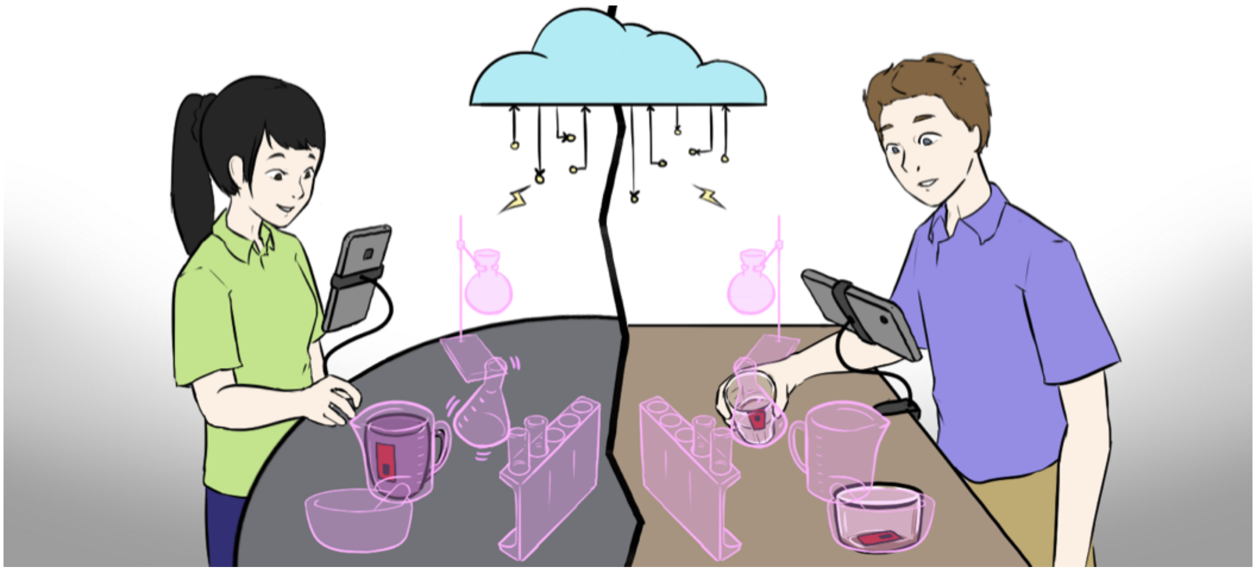


Figure 4.1. Overview of the usability of our toolkit to enable remote collaboration in a TAR laboratory. Each module includes a fiducial marker, Arduino Nano, and a haptic driver for customizable haptic feedback. Students collaborate remotely by using tangibles that are proxies to virtual objects.

This chapter is presenting work published at the ACM Conference On Computer-Supported Cooperative Work And Social Computing [176].

We propose combining AR with the capabilities of TUIs to leverage haptic feedback, improve local and remote user experience, and provide a sense of presence to spatially distributed users. In this work, we propose the hardware and architecture to facilitate remote collaboration between students. We aim to enrich the local and remote user experience by providing users with customizable and shared haptic feedback, and enabling the coordination in both the AR content and procedure of the laboratory. We consider it timely to propose the toolkit to enable AR and haptic-based remote collaboration in TAR laboratories. Thus, we design, develop, and assess ColabAR (Fig. 4.1), and present the follow contributions:

1. **An approach to introduce customizable haptic feedback interaction techniques for remote collaboration in TAR laboratories**.

2. **A toolkit for prototyping of TAR laboratory experiences.** The physical props are made from everyday objects and the hardware enables direct manipulation of the virtual world. We include a remote collaboration architecture to support sharing of AR content and haptic information.

3. **Usability study and performance evaluation** to validate and test the effects of our toolkit in enriching local and remote TAR laboratory experiences.

4.1 Related Work

4.1.1 TAR Laboratories for Remote Collaboration

In this section we describe previous work used to develop distance laboratories. This is the research we reviewed in order to benchmark our ColabAR project, a toolkit to create TAR laboratory experiences. Aside from exploring AR, we explore the use of haptic feedback to add an extra layer of interaction between participants.

4.1.2 Haptic Feedback

Many TUIs utilize physical objects to provide haptic interaction with mixed reality interfaces [177]–[179]. Combining AR with TUIs creates a Tangible Augmented Reality (TAR) setup, which can use haptic feedback from physical objects and uses AR as the virtual interface to the physical world. This approach is useful in our context–to simulate laboratories with expensive real-world equipment–because physical objects, which act as proxies to virtual counterparts, have familiar properties and physical constraints. Thus, these objects are easier to use as input devices [179], [180]. Currently, the tactile approach is one of the most commonly used for haptic feedback techniques [181]. For example, vibration on our smartphones or game controllers enables cutaneous perception of a text-message, or a car crash in a video-game. Vibration motors have become easily accessible given their miniaturization and simple design, which allows for their implementation as a haptic technique. Past work has evaluated the benefits of audio and tactile feedback to facilitate communication [182], [183]. They have also been used to deliver different feedback such as confirmations of received messages, error warnings, and download progress reports [184]. In these cases, different vibration patterns, such as rate, duration, and strength, improved the resolution for haptic information transmission [183], [185], [186], the vibro-haptic experience [187], and user immersion by providing appropriate intensity and roughness [188]. However, the aforementioned haptic techniques for AR included the vibro-tactile feedback into the AR delivery device (e.g., smartphone, wristband, headband, etc.), which impedes direct object manipulation of tangibles in the scene; while the audio feedback is innate to an AR-compatible device, since it can be obtained from the phone's speakers. In our toolkit, we decouple the feedback modules from the phone, instead placing a module on the surface of each tangible. We hypothesize that combining inertial measurement unit (IMU) sensors and vibration feedback into a single module will enable a richer haptic experience. Thus, we leverage readings from the IMUs–during users' direct manipulation with the physical props–to generate customizable vibro-tactile feedback.

4.1.3 Remote and Virtual Laboratories

Remote and virtual labs have the potential to lower costs of equipment and maintenance of in-person labs, while leveraging students' tech-savvy intuitiveness [189], [190]. Empirical results have reported that virtual and remote labs provide comparable academic performance and curiosity. Past work has shown that properly planned and delivered virtual labs can increase students' knowledge, skills, and performance in examinations; while facilitating distance learning, promoting health and safety, and reducing cost of performance to traditional in-person labs if the content is carefully curated [191]–[200]. Some other benefits cited by these authors include the availability of these labs at any time, unlike physical labs which are typically only available for short periods of time due to logistic accommodations. Also, scientific inquiry usually requires iteration of an experiment [201], [202], which is simplified by virtual labs.

Virtual labs, which take place in the digital world, support a wide range of subjects involving thermodynamics [203], chemistry [204], electricity [205], [206], physics [207], biology [208], [209], fluid mechanics [191]. Virtual labs are also useful tools to facilitate pre-laboratory preparation and make sure that students get exposed into how to handle equipment and perform an experiment [210], [211], which is an essential part of the laboratory learning experience [212], [213]. Remote labs, in which students handle actual physical equipment and obtain real-world data, allow for experimentation that would take place in hands-on labs. Thus, students get an opportunity to understand real-world experiments, including measurement errors and unpredictable outcomes [207], [214]. These labs have been implemented in different domains of high complexity, such as control engineering [215]–[217], spectroscopy [218], [219], thermodynamics [203], robotics [220].

Remote labs allow for hands-on learning, but still require physical equipment which incurs in maintenance and scheduling. Virtual labs solve the issue of scheduling conflicts and equipment upkeep, but lack hands-on learning. Our toolkit for AR-based labs aims to use the best features of virtual and remote labs: TAR experience provides hands-on learning by adding virtual information overlaid on the physical objects in the scene, and enable students to practice as often as they like, without taking up resources. Additionally, we focus on providing a cloud architecture to share virtual information and haptic feedback to enrich collaboration.

4.2 Elicitation Requirements

In order to enable TAR laboratories for STEM distance learning, we need to find out what unique challenges we have to overcome to deploy a laboratory at home–in particular–using AR. We interviewed 3 laboratory instructors and 10 students who had at least one year of experience in laboratory courses in Chemistry and Physics. Two instructors had at least 2 semesters of experience teaching Chemistry for Engineers and the other instructor had 3 semesters of experience teaching Circuits and Electronics. We prepared a semi-structured interview with the instructors to understand what valuable experiences needed to be mimicked from the physical world and what to leverage from the augmented setup to enrich students' experience. Each interview was individual and lasted from 30 minutes-1 hour. Students responded to a survey completed voluntarily.

4.2.1 Findings

Instructors were mostly concerned with recreating the practical aspect of handling science equipment. There was a consensus that concepts taught during a lecture were better understood through scientific experimentation. Also, instructors considered that this type of exploration was the closest experience to the real world situation they could provide for their students (e.g., chemical reactions, current flow, collision). Students were more concerned with a flexible setup that is simple to implement, while providing enough room to change and tune parameters within the experiments and obtain different results. Although students had little experience with virtual laboratories, they were excited by the prospect of freely exploring a laboratory setting without the fear of breaking or damaging any equipment. Thus, based on these observations, we decided on design goals for our toolkit.

D1. A need to support a complex environment. A toolkit for TAR laboratories needs to support equipment which matches the complexity and variety of real-life physical laboratories. Students pointed out that depending on the course, they had access to different machinery, handheld objects, tools, and other tangibles. Thus, bringing them home physically would not be possible, but if the environment was built virtually, then laboratory activities were possible regardless of location.

D2. A need for new techniques for communication. A TAR system needs to generate techniques to successfully share non-verbal cues between participants. Instructors pointed out that students often depend on their lab partners' guidance to understand concepts that are new or difficult. Moreover, they rely on their lab partners for help if they get stuck at any point in the experiment.

D3. A need for empathetic collaboration. While laboratory partners are interacting remotely, we need to make sure that help and instructions are shared organically between them, with a focus on the audiovisual and tactile sensory channels. Both instructors and students coincided that collaborative work within an augmented laboratory should still provide users with sense of presence and immersion. More importantly, we have to capture the physical presence of the users into the AR world in such a way that we continue providing interactions between distant users.

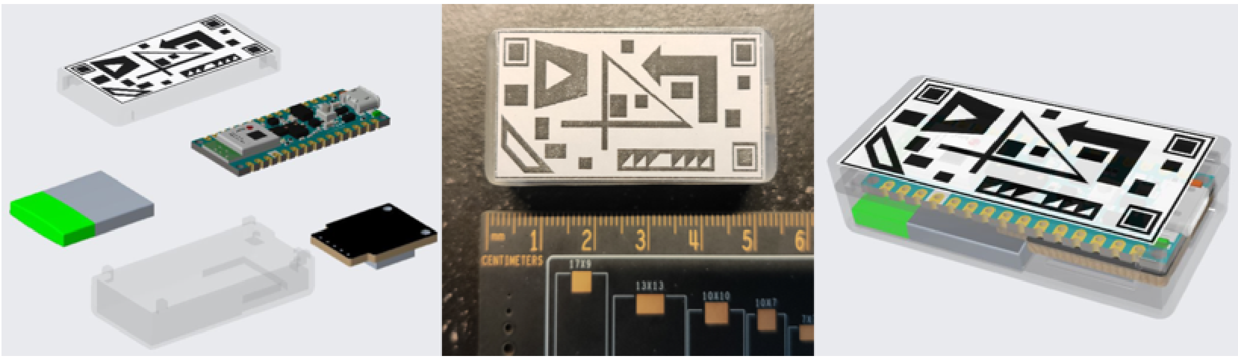


Figure 4.2. *Left*: Explosion CAD view from haptic module of ColabAR, includes: encasing with fiducial marker, Arduino Nano, haptic driver, and battery. *Middle*: Tag and ruler(cm) for scale. *Right*: Tag Assembly.

D4. A need for augmentation beyond physical limits. We need to successfully correlate physical proxies and their virtual counterparts, and also extend their functionalities beyond what is possible in the real world. Instructors were interested in utilizing less resources while allowing students to engage in more versions (i.e., different conditions) of a same experiment. Students were optimistic about the possibility in engaging in augmented laboratory work but were apprehensive as to how their performance could be maintained in completing experiments. However, they considered their performance could also be improved given the possibility of practicing or finishing laboratory work outside of the constraints of a scheduled and supervised laboratory session.

D5. A need for scalable architecture. We need to leverage cloud capabilities to enable multiple users to simultaneously take part in a laboratory, even if these are split in pairs. Instructors indicated that any lab session they create for their students should be accessible and easily implemented by students.

4.3 System Overview

4.3.1 Hardware

Haptic Module

The haptic module is shown in Figure 4.2.

We used the DRV2605L haptic driver breakout with linear resonant actuator(LRA), to render fine-grain tactile vibration. The small range of resonant frequency of LRA guarantees stable vibration at various amplitudes. The low haptic response time allows the LRA to be sensible to input signal (start-up time is around 0.75ms and typical rise time is around 10ms), which is the key to generate authentic haptic feedback. The Arduino Nano 33 BLE Sense board includes an nRF52840 processor and a 9-axis Inertial Measurement Unit (IMU). The nRF52840 processor contains a powerful Cortex M4F and integrated Bluetooth Low Energy (BLE) Radio. The BLE protocol allows us to connect the toolkit with the phone at low power consumption. The connection latency has a minimum of 5ms. The IMU–which measures the angular velocity and acceleration–has an update frequency of 952Hz. It captures the module's movement constantly in real time, so as to enable more responsive feedback to be provided accordingly. We used a 150mAh Lithium Polymeter battery which allows the toolkit to work continuously for about two hours without recharging. All these components are encapsulated in a (48mm*23.5mm*13mm) sized 3D-printed case. On the external surface an AR fiducial marker–used for camera tracking was attached. The whole haptic module weights 19.8g and costs around $30. The modules were attached to the real-world objects through double-sided tape, which proved to be sufficiently stable.

Smart Phone

In our setup, Android phones are used both to render/display AR content and to control haptic modules. The use of the Android phones is optional as they could be replaced by students' own smartphones, as long as these were AR-compatible.

4.3.2 Software

Unity Package

We provide a *Unity Package* for content designers to easily author varied types of haptic module behaviors and integrate them seamlessly to an existing AR application. The interface of the package is shown in Figure 4.3 (Left). Each haptic module with AR marker attached is in one-to-one correspondence with an *Unity Prefab* (see Figure 4.3: Top-Left). The authoring process begins with clicking on one of these prefabs, after which users are prompted to choose from three types of haptic feedback (see Figure 4.3a). Each haptic feedback comes with customizable options (see Figure 4.3a-c) to meet with diversified demand. Details on these types of haptic feedback will be illustrated in the next section.

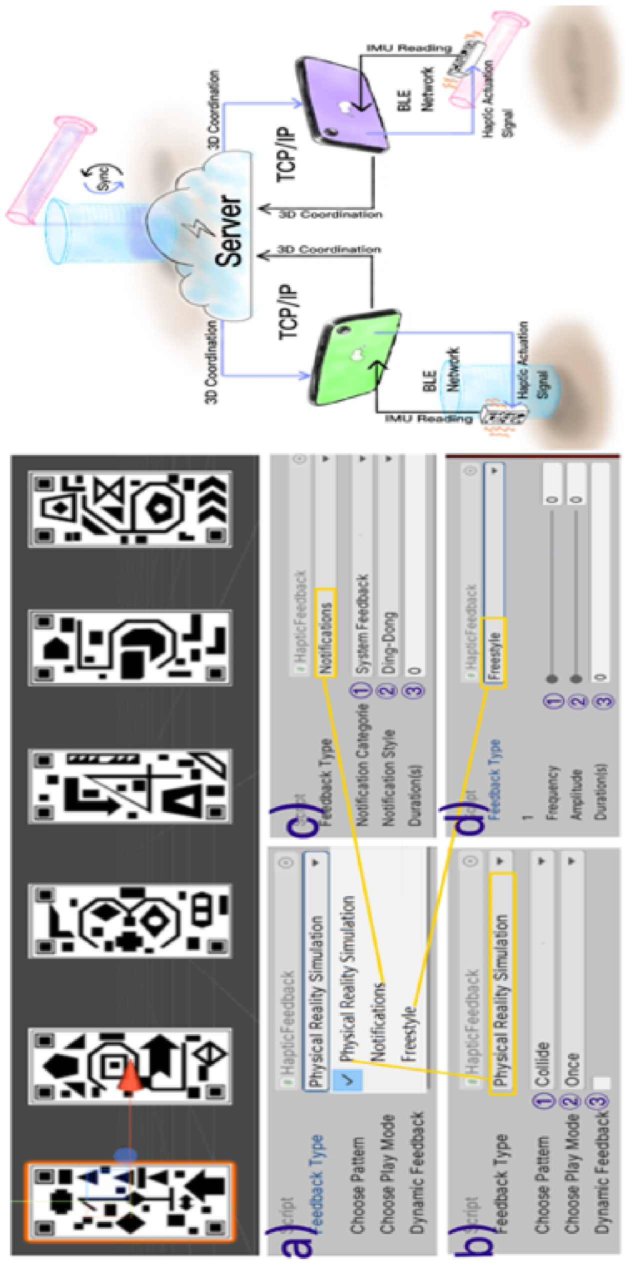


Figure 4.3. *Left:* Unity package interface. *Right:* System diagram of the multi-tier network.

Network Architecture

We adopted a tree topology, as shown in Figure 4.3 (Right) to construct the multi-tier network architecture which connects the haptic modules, phones and the remote server together.

On the lower tier, haptic modules are linked to the phone through the Bluetooth Low Energy (BLE) network. The BLE network can operate with low energy consumption which is crucial for our self-contained module. On the upper tier, phones from different users are connected to each other through an intermediate server. The TCP/IP protocol is used in this tier to ensure reliable data transmission between phones. After connecting a module to the phone, it starts sending periodical IMU sensor data, while receiving haptic actuation signal simultaneously. Meanwhile, the phone sends the real-time 3D coordination of the local module to the server to be synced and forwarded to its remote counterpart.

4.4 Haptic Feedback

Haptic feedback has been shown to be effective in conveying information to the user when used in conjunction with visual feedback [221]. We leveraged haptic feedback for the following categories:

4.4.1 Physical Reality Simulation

We utilized haptic feedback to provide a more realistic user experience inside the TAR laboratory. The goal is to provide the illusion as if physical properties and constraints still persist when interacting with virtual objects. To this end, we took from the suggestions of the experts in *Elicitation Requirements* section. Thus, we designed physical events which occur frequently during lab sessions and generalized seven physical built-in patterns (see Figure 4.4a-g)–"Collide", "Dock", "Switch", "Knob", "Electric Current", "Chemical Reaction", and "Liquid Flow". We sampled the sounds of each event in real world, analyzed the sound wave spectrum, and tuned a similar shape vibration waveform accordingly through altering the amplitude of LRA. By doing so, we derived high fidelity feedback to represent those patterns. Figure 4.4 (Bottom-Left) shows an example of how we encode "Dock" from sound to a haptic signal.

These converted feedback will be triggered under specific circumstances to provide users with better perception of the environment. For instance, during remote collaboration, both parties are constantly interacting with virtual objects, which are proxies of the physical module on the other side. Past work has shown that users who experience AR on their phones often find it hard to tell exactly how close or how far the virtual object is which makes the interaction process difficult [222]. This lack of depth perception can be mitigated by adopting "Collide" feedback whenever the module makes contact with a virtual object. Users now can both see and feel where the virtual objects are. To further achieve a higher level of realism, the magnitude of the haptic feedback can be dynamically altered according to user's action intensity. The angular velocity and acceleration readings from the IMU are leveraged for calculating the gain value for the dynamic adjustment. For instance, when a rod is used to stir liquid, the corresponding module triggers the "Collide" feedback, as if the rod is hitting the wall of the beaker. To make the vibration dynamic, We let the vibration gain to be: λa, where a is the acceleration obtained from IMU and λ is a constant scaling factor. This mimics physical world circumstances, in which the force is proportional to acceleration.

4.4.2 Notification Feedback

Haptic feedback can also serve as notifications, which augment users' awareness of hints and cues in the virtual world. We establish two categories of notification feedback–*System* and *Partner*. They share four haptic notification style –"Ding-Dong", "Beep", "Interval", and "Non-Stop". The vibration waveforms spectrum can be find in Figure 4.4 (Bottom-Right).

System feedback

Notifications which convey positive, negative, or suggestive haptic feedback based on user's inputs are defined as system feedback. System feedback is pre-defined by the content

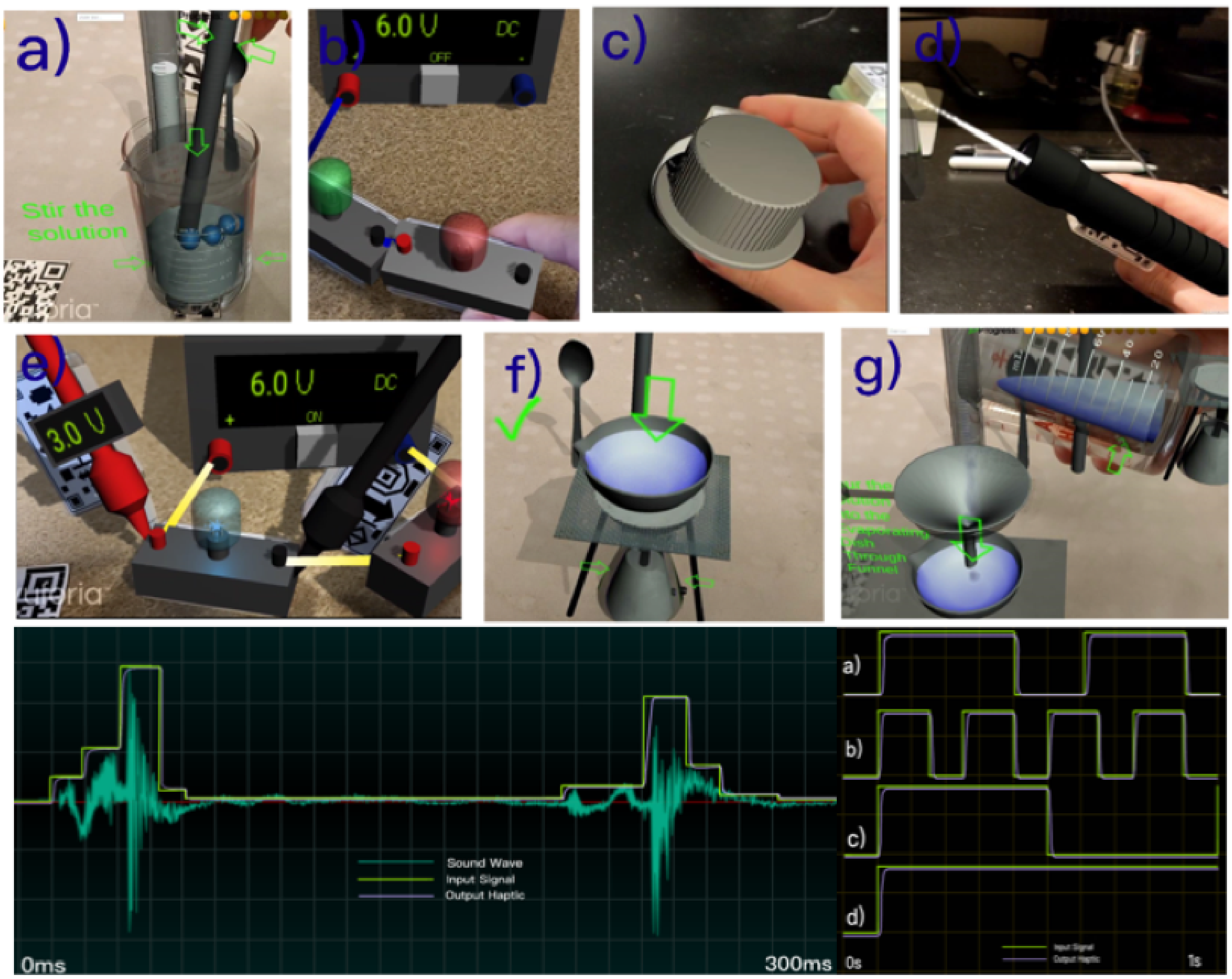


Figure 4.4. *Top:* Haptic feedback triggered in various situations:(a) "Collide", (b) "Dock", (c) "Switch", (d) "Knob", (e) "Electric Current", (f) "Chemical Reaction", (g) "Liquid Flow". *Bottom-Left:* Conversion from sound to haptic signal. *Bottom-Right:* Vibration waveform spectrum of notifications feedback: (a) "Ding-Dong", (b) "Beep", (c) "Interval", (d) "Non-Stop"

designers, with in-built hints and warnings. The duration of the feedback is chosen as per designers' preferences.

Partner feedback

Synchronous collaborative tasks require participants to maintain an awareness of their partner's cues and activities, as a necessity for effective inter-personal communication. Spatial tactile feedback can reduce the overload of information visual and audio space. Partner feedback is actuated by one user to inform his or her partner. In our case, vibration conveys the message of a notification, which is used by a student to help his or her partner in finding the correct object. The duration of the feedback is set by users' preferences.

4.4.3 Freestyle Feedback

We enable content designers to create their own sequential haptic feedback as the means to open the door for more creativity. They can design up to five different haptic patterns in sequence. For each pattern, there are three variables for adjustment: frequency, amplitude, and duration Figure 4.3d. Frequency represents the interval between every single vibration and can be set from no vibration (0Hz) to continuous vibration (around 300Hz). Amplitude represents the magnitude of vibration in a range from 0g to 1.4g. Duration represents the time length of the pattern. Both frequency and amplitude are fitted into a hundred percent scale for better perception.

4.5 AR-only vs. ColabAR Evaluation

We performed a within-subjects user study to determine the validity and effectiveness of our toolkit, which supports hands-on learning through a TAR framework. As we previously explained, audio and visual cues are innate to AR, while our haptic feedback requires implementation of a hardware module (external). Thus, our experimentation exposes participants to two conditions: (a) AR only, (b) AR with haptic feedback (ColabAR implementation). The order by which we provided condition (a) and (b) was randomized to avoid bias in participants. ColabAR aims to facilitate the remote collaboration experience by providing

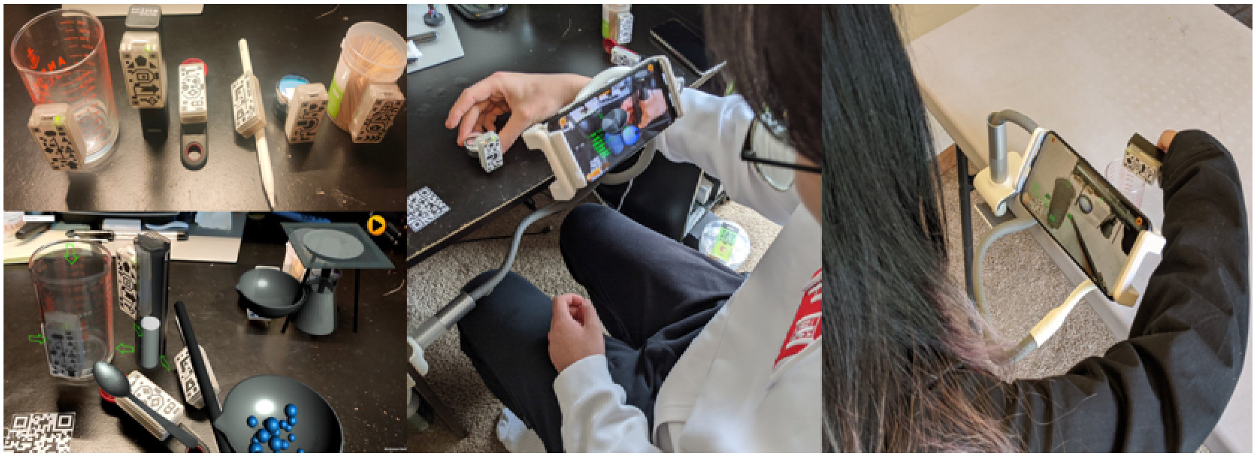


Figure 4.5. User study overview: (*Left*) (Top) Example of physical props used for Organic Chemistry TAR laboratory. (Bottom) AR superimposed on the tangibles. (*Middle, Right*) Students collaborate remotely and send each other feedback.

haptic feedback during direct manipulating of tangibles in an TAR laboratory. The purpose of this evaluation was made to analyze students' reactions to the technology and gain knowledge into how the toolkit facilitated collaboration between laboratory partners.

4.5.1 Setup

For this experiment, we chose a Chemistry laboratory (Fig. 4.5) for our implementation. We wanted the laboratory to be based on an advanced curriculum for undergraduate students, so we implemented an Organic Chemistry Laboratory on *Purification of Solids by Recrystallization* (as an example, see [223]). We selected this particular laboratory for the following reasons: (a) Chemistry laboratory equipment conveniently aligns with use of tangibles in AR for hands-on learning; (b) Chemistry laboratories are typically performed collaboratively.

Each participant was in a separate room, but the laboratory was done in pairs. This laboratory took about 65 minutes: 15 mins. for pre-lab, 20 mins. per condition, and there was a short break (5-10 mins.) in between. There was at least one researcher physically present with one participant, while each participant had a full view of the virtual world (i.e., collaborative laboratory) of the other's environment through the phone (Fig. 4.5, left).

Researchers provided three daily objects (e.g., a glass, a battery charger, a spoon) for one user and three objects (e.g., an Apple pencil, eye cream bottle, tooth pick container) for the other, because this laboratory required 6 pieces of lab equipment and these objects were proxies for the lab equipment. We attached one module to an object using double sided-tape and then connected via Bluetooth. The dynamics of collaboration were as follows: if a participant has the physical object required for a step, then he or she completes the step. For example, step is to pour solution into beaker: participant A has the flask with the solution while participant B has the beaker; participant A completes the physical action of pouring the solution.

The study began with a pre-lab session, which included an interactive tutorial to learn the capabilities of the AR and the haptic feedback from the tangibles in the scene. After this initial pre-lab session, participants were able to understand the basics of AR and direct manipulation using tangible devices as input.

For AR-only condition (AR), participants were able to communicate and observe each other's movement inside the AR scene (i.e., shared audio and visual cues). For AR with haptics condition (AR+H), participants had the same setup as the AR-only condition, with haptic feedback added from the vibration motors. For participants to go from one condition to another, we turned the Bluetooth connection from the modules on or off.

The lab session included users working through the experiment's procedure. Instructions for each step of the lab were shown on the phone's screen. These instructions were taken word-for-word from the undergraduate curriculum.

4.5.2 Participants

We recruited 20 participants (8 male, 12 female) ranging from 20 to 28 years old (M=21.7, SD=1.9), based on background and experience. All of our participants were undergraduates at our university and had a STEM major. Each pair of participants working together already knew each other. We did not have access to a real laboratory; however, we made sure that our participants had previous experience with physical laboratories, so that their answers and comments could compare our TAR laboratory to their real world experience. All of our subjects had considerable experience with STEM physical laboratories (M=4.6 years, SD=1.9). 11 participants had prior experience with smartphone AR systems, but none had any experience with direct manipulation of tangibles in an AR scene.

4.5.3 Results

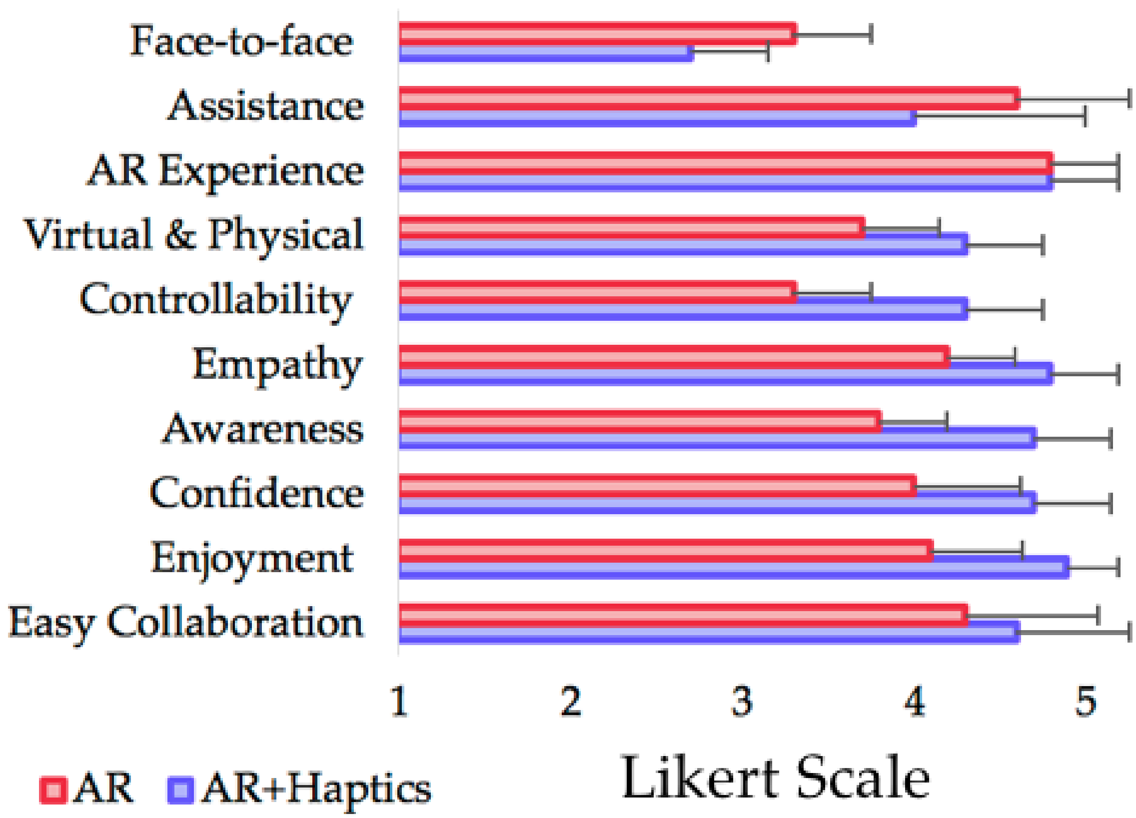


Figure 4.6. Results from average scores on the usability of AR, haptic feedback, and collaboration experience for all participants. Blue: AR+Haptic feedback condition, Red: AR-only condition. We used 5-point Likert scale (1-strongly disagree, 5-strongly agree.

Following the laboratory session which was successfully completed by all participants, we presented the students with a 5-point Likert scale (1-strongly disagree, 5-strongly agree). The survey evaluated the usability of AR, haptic feedback, and collaboration experience. Figure 4.6 shows the average scores reported by students. We collected the results for the following questions: Q1: "*It was easy and successful to collaborate together*"; Q2: "*I enjoyed the collaborative work*"; Q3: "*I felt confident during the laboratory*"; Q4: "*It helped me feel aware of my partner*"; Q5: "*It helped me feel empathy towards my partner*"; Q6: "*I felt in control of the experiment*"; Q7: "*It was easy to correlate virtual and real objects*"; Q8: "*I liked the AR of the experiment*"; Q9: "*Assistance is provided in real-time*"; Q10: "*I prefer face to face interaction with my lab partner*".

As we explained previously, our study compares participants under two conditions: AR-only vs. AR with haptics. We started with a Shapiro-Wilk normality test to verify that the normal assumption was not met. Then, we performed the Wilcoxon-signed rank test, the equivalent of the nonparametric paired t-test (Fig. 4.6). When comparing both conditions, we found several questions for which differences between conditions were statistically significant ($p<0.05$). The haptics (M=4.9, SD=0.3) provoked greater enjoyment in the distant work than AR-only (M=4.1, SD=0.54) [Z=-2.53, p=0.01]. The haptics (M=4.7, SD=0.46) produced greater confidence in the laboratory procedure than AR-only (M=4.0, SD=0.63) [Z=-2.33, p=0.02]. Similarly, the haptics (M=4.7, SD=0.46) enabled greater awareness of the partner than AR-only (M=3.8, SD=0.4) [Z=-2.46, p=0.01]. Also, haptics (M=4.8, SD=0.4) produced more empathy with the partner than AR-only (M=4.2, SD=0.4) [Z=-2.49, p=0.01]. As for specific interactions enabled by the system, the haptics condition (M=4.3, SD=0.46) made it easier to correlate virtual objects and their physical counterparts than the AR-only (M=3.7, SD=0.46). Finally, we found that the AR-only condition (M=3.3, SD=0.46) made it more likely for students to prefer for face-to-face interaction than the haptic condition (M=2.7, SD=0.46) [Z=-2.449, p=0.01]. For the remaining questions, we found no statistically significant differences between conditions ($p>0.05$).

We also interviewed students on their experience. We had the advantage that they all had considerable exposure with physical laboratories, so they could compare them to the hands-on TAR experience we provided. In the discussion section, we will explain the criteria behind survey's responses, based on students' comments and experiences.

Figure 4.7. User study overview: (*Left*) (Top) Example of physical props used for Organic Chemistry TAR laboratory. (Bottom) AR superimposed on the tangibles. (*Middle, Right*) Students collaborate remotely and send each other feedback.

4.6 Zoom Lab vs. ColabAR Evaluation

We conducted a between-subjects user study to measure performance, time, and usability of a TAR laboratory implemented using our toolkit. For this user study, we decided on a more realistic approach following the way laboratories have been continued at a distance in some universities. Thus, we expose our participants to two conditions: (a) *AR with haptic feedback*, full implementation of our ColabAR toolkit; (b) *Zoom videoconference*, including physical components of the laboratory. In both instances, the technology (AR or Zoom) was used to enable collaboration between laboratory partners.

4.6.1 Setup

We borrowed from the curriculum of a *Circuits and Programming* class to test our implementation for a laboratory session. We selected this laboratory due to the following logic: (a) circuitry has been one of the few laboratories that did not get cancelled and were able to be continued at a distance; (b) some instructors provided their students with circuitry kits, so they could keep working on the lessons with these physical components; (c) we had access to the curriculum, instructor, and physical components that made up the class. In our case, the instructor/developer implemented the laboratory in Unity using our toolkit. The instructor reported that creating the AR environment (assets and animations) took approximately 7 hours, while implementing the haptics using our toolkit only took him approximately *30 minutes*.

During our laboratory session on *DC Circuits* we introduced and then tested our students to the following concepts: (a) *circuit components, connections, and measuring tools*; (b) *connections in series and parallel*; (c) *power supplied and dissipated*. For the Zoom condition, we provided the physical equipment required for the laboratory and the phone for videoconferencing (Fig. 4.7, left); while for the AR with haptics condition the setup was similar to our first user study (Fig. 4.7, right). Since Zoom condition had no AR to deliver the instructions, we provided participants with written instructions. The session split was as follows: pre-lab and lab session. The 20 participants were divided into pairs, but each pair only completed one condition, since this was a between-subjects study.

In this user study, we wanted to focus on students' performance at the laboratory session. Students had a more exploratory setup in which to *understand voltage and current*, *make several circuitry connections*, *take multiple measurements*, *add variations to those connections*, *draw diagrams*. For both conditions we provided a lab worksheet with questions and exercises, which participants had to complete and turn in for grading.

4.6.2 Participants

We recruited 20 undergraduate students (10 male, 10 female) ranging from 20 to 25 years old (M=21.65, SD=1.62). This set of participants were different from our previous user study. All but two participants did not have background in electrical circuitry and were not majoring in a STEM career. Each pair of participants working together already knew each other prior to the experiment. The instructor in charge of content creation and grading had more than 2 years of experience in electrical circuitry classes and workshops.

4.6.3 Results

In this section, we compare two conditions: Zoom+Physical Components vs. AR+Haptics. We performed the Shapiro-Wilk test to validate the normality of our data. Since this assumption was violated, we evaluated our data using Mann-Whitney U Test.

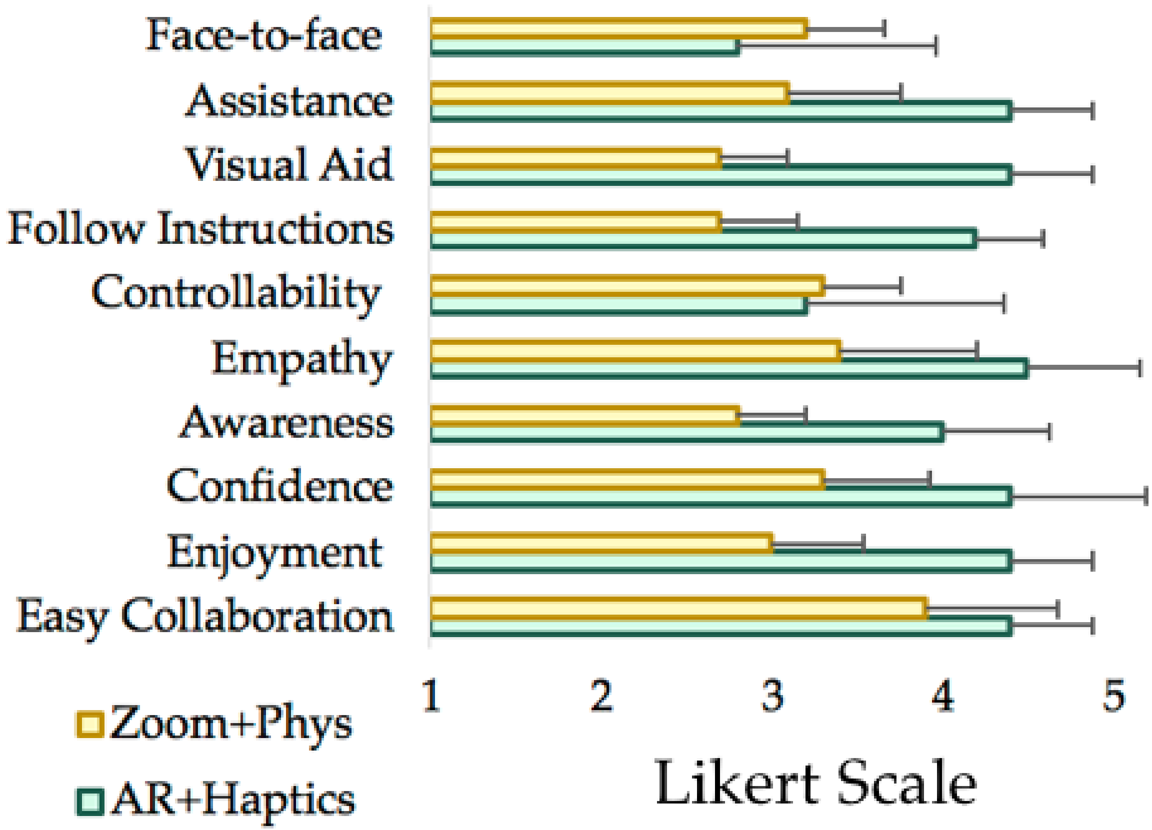


Figure 4.8. Results from average scores on the usability and collaboration experience for all participants. Green: AR+Haptic feedback condition, Yellow: Zoom+Physical components. We used 5-point Likert scale (1-strongly disagree, 5-strongly agree.

After the lab session was completed and the lab manual was turned in by participants, the instructor graded the worksheets from both groups. The grades of the lab manuals provided by the instructor are our reported performances scores. The instructor scored each answer with a 0 if incorrect, +0.5 if answer had some substance, or a +1 point if correct. Then, the total points were normalized to fit into the 1-point scale. Instructor was the primary coder and reviewed all lab worksheets. Inter-rater reliability on scoring was validated by having a secondary person grade over 25% of the data. From our rubric, the instructor and the researcher in charge of grading had a Cohen's Kappa of 0.68. The results showed that for AR+Haptics (M=0.85, SD=0.05) and Zoom+Physical Components (M=0.87, SD=0.07) there was no statistically significant difference between grades ($U=39$, $p>0.05$); however, both groups were scored highly by the instructor and were able to performe the laboratory satisfactorily.

In terms of time to complete the experiment: AR+Haptics (M=81.2 mins, SD=4.71), Zoom+Physical Components (M=60.8 mins, SD=4.26). The decrease in time (25.2%) was statistically significant between conditions ($p<0.05$).

With respect to the usability questions (Fig. 4.8), several had differences between conditions which were statistically significant ($p<0.05$). The haptics (M=4.1, SD=0.7) provoked greater enjoyment in the lab experience than Zoom (M=3, SD=0.54) [U=15, p=0.007]. The haptics (M=3.9, SD=0.7) produced greater awareness of the partner than Zoom (M=2.8, SD=0.4) [U=17, p=0.011]. As for specific interactions enabled by the system, the haptics condition (M=4.2, SD=0.6) made it easier to follow instructions than Zoom (M=2.7, SD=0.46) [U=15, p=0.007]. Visual aid was also preferred under the haptics condition (M=4.2, SD=0.75) than Zoom (M=2.7, SD=0.4) [U=10, p=0.002]. Finally, the quality of assistance was considered better with haptics (M=4.1, SD=0.54) instead of Zoom (M=3.1, SD=0.66) [U=13, p=0.004]. However, the haptics (M=3.4, SD=0.66) produced less empathy for the partner than Zoom (M=4.5, SD=0.81) [U=19.5, p=0.019]. For the remaining questions, we found no statistically significant differences between conditions ($p>0.05$).

4.7 Findings

4.7.1 AR-only vs. ColabAR

Our experiment aimed to understand whether haptic feedback in a TAR laboratory enriched the collaboration experience. To this end, we chose to replicate an Organic Chemistry Laboratory.

We begin by explaining students' first impressions on the setup under both AR-only (AR) condition—which allowed students to see what their partner was doing inside the AR scene and listen each other—and AR with haptic interaction (AR+H) condition–which provided the same functionality as AR-only condition, but also included haptic feedback from the vibration driver attached to the physical props.

Consensus among participants was that they preferred the combination of AR (visual cues and audio) with haptic feedback (AR+H). Using our toolkit, we provided participants with 3 types of haptic feedback: Physical-reality simulation feedback, Notification feedback, Freestyle Feedback. Both conditions (AR and AR+H) scored highly for successful collaboration overall, and participants commented that some types of haptic feedback were more intuitive than others; while visual cues, in general, were easier to process.

Notifications feedback gave warnings or hints was already pre-defined for the AR scene, so it was provided to the participants as they moved along with their experiment. Subjects liked this feedback because it stopped them from making mistakes, especially as they were considering how it would translate to keep them from choosing wrong apparatus or substances in a real-world scenario. This type of feedback seems to have increased the confidence within participants regarding the control of laboratory work.

The add-in haptics made the collaboration smooth, but above that I can always find the items and objects I am looking for.–P17

Added system haptic feedback was perceived as a positive complementary feature to the shared audio of participants. This feedback was used by participants for specific hands-on help when participants were not verbally responding or were stuck at any part of the experiment. As explained, voice communication was the go-to, intuitive method of communication, but participants reported that the haptic feedback added *"another dimension"* (P16) to the collaborative process. For example, it could be used by students to softly let their partners know that they were done working with a certain apparatus.

The vibration is useful and I really liked using that feedback to signal to [my partner] by clicking on the screen decreased confusion.–P4

Physical-reality simulation type of feedback was considered as the most *"enjoyable and realistic"* (P8) feature in the TAR system. As we previously explained, we leveraged readings from the IMU modules to provide customizable feedback in terms of frequency vibration based on tangibles manipulated by participants. This type of feedback improved the individual's experience and awareness of his or her partner in using the TAR laboratory.

I liked the real-life mimicking of the actual thing because it wasn't that different from the real lab experience.–P5

I've done some virtual labs before, but this is my first time actually involved in a hands-on [TAR] lab. You can do the motion of picking things up, stir the solution, pour water. It feels very real!–P14

I knew it wasn't the real thing, but I felt like I was doing the real thing.–P9

System feedback–a category under Notification feedback and pre-defined–was considered useful for the collaborative experience but not intuitive towards the individual experience. It usually had to be coupled with Partner feedback–a category under Notification feedback but with duration control by the partner–or verbal communication. The purpose of this feedback was to allow students to correlate a physical object with its virtual counterpart. For example, if a participant was not sure of which physical object was the proxy of a virtual object, he or she could simply tap on the virtual object and received a vibration from the physical object. Participants typically reminded their partners of this feature, but it was difficult for their partners to remember this functionality while they were manipulating objects in the scene.

This [system feedback] haptic functionality is useful, but sometimes I would forget to use it, until [my partner] would make it vibrate, and I would be like "Oh, this is the wrong [beaker]!"–P1

We consider that a multi-session exposure to our system could possibly make system feedback a stand-alone or, as one participant suggested, we could add a feature to change the opacity of the virtual object superimposed to make the physical object more realistic. This suggestion, however, could take away from the immersion of the scene.

I liked the haptic feedback but I think I'd prefer for the opacity to be adjusted so models don't overlap with each other.–P12

Participants considered our TAR laboratory to be a better alternative to the AR only, especially to share information. Several students liked the option of being able to perform laboratory sessions from home. Most students referred to scheduling conflicts and safety as important reasons to work using remote collaboration. A few participants commented on a short lag in the virtual environment, but reported that it was not significant enough to take away from the experience.

AR content lacks some physical information but haptics is a great addition to the physical information.–P7

4.7.2 Zoom vs. ColabAR

As we previously mentioned, we focused on the performance of the students in the laboratory.

In terms of remote work, one of these options (AR+H) offers the possibility of different experimental setups, as well as a cheaper alternative including avoiding the purchase of the physical equipment. However, our main concern was whether handling these proxies (AR+H) would have comparable results to the physical elements (Zoom+Phys). Our results demonstrated that students' performance was positively comparable for both conditions. However, in terms of time to complete the experiment, AR with haptics required considerably less time to complete all exercises when compared to Zoom videoconferencing with physical elements. It seems like this is due to the *physical-reality simulation* feedback mimicking and amplifying real world responses between components (e.g., bulbs making contact with the power source and with each other). Also, *notification* feedback enabled users to know whether they had connected the bulbs in the wrong direction. Similarly, this feedback was used for partners to send warnings to each other (e.g., when a bulb was missing from the circuit; when a bulb had been added in series rather than parallel as the manual requested; when the setting in the multimeter was on measuring current rather than voltage and viceversa as the exercise requested; when measuring probes of the multimeter were being used to measure mistaken points on the circuit).

The AR coupled with the haptic feedback allowed for an improvement in working collaboratively in less time than the Zoom videoconferencing. Similarly, in terms of user experience, the immersion of AR with haptics provided significant improvement in getting and providing help between partners. As students worked on the laboratory, participants can use videoconferencing (Zoom+Phys) to demonstrate or point to their circuitry work; however, there were several problems with focusing and moving the phone camera around to show the scene and even then, help with problem-solving was mostly descriptive between participants. One benefit of haptics (AR+H) is that the help is in-situ, so students do not have to find the right camera angle to show their work; instead, all they have to do is send *notification* feedback to lead students to the correct area in the circuit. This feedback coupled with their shared

AR environment, is used to provide hands-on help. As for videoconferencing (Zoom+Phys), students would change between the front and the back camera, so that it would sometimes focus on the workspace and other times on their own faces, and this did seem to have a positive effect in empathy during collaboration. Camera switching may not be a stable idea to include in an AR environment due to loss of tracking; however, it may be interesting to explore a cohesive way to implement it as a future option.

Finally, as the performance evaluation between physical objects and proxies seems to be comparable, we see great potential in deploying our toolkit for designers and instructors to create their own TAR laboratories. Our approach creates a rich experience by combining haptic feedback into a learning environment for remote collaboration. This scenario requires interaction techniques that supplement in-person laboratories (e.g., as a tool to create pre-labs) and partnership.

4.8 Discussion

4.8.1 Strength of Haptics in Collaboration

The first research question in this paper was to analyze whether implementation of haptics improves the user experience of distant collaboration. Based on our results, haptics received significantly more positive feedback than the non-haptic conditions due to the following reasons.

State of Interaction.

When going about the laboratory process, one of the main challenges for the participant is to establish a strong sense of co-presence and engagement with his/her partner. Physical presence will always be the gold standard of interaction; about half of participants reported that vibrotactile patterns were too smooth to be human-like, but they appreciated the variety of the patterns and the awareness they provided with the knowledge that it was activated by a human on the other side. This ‘activation’ of the feedback provides an additional layer of interaction that seems to enable a ‘negotiation’ through this non-verbal information, in which a participant is highly in-sync with the status of the other and what new information needs to be provided. Thus, in the case of semester-long recurring lab partners, we would strongly recommend instructors allowing students to allow for flexibility and choice for which haptic patterns will be established between partners.

Control Trade.

Setting up this collaborative experience makes sense if we can ensure a superior joint efficiency of the partners. Similar to a physical laboratory in which a participant tends to guide the other, haptic feedback provides the illusion that a participant is helping the other with the execution of a task. This illusion works as long as one participant is not providing too much help or receiving too much cumbersome stimuli. In our experiments, the roles of the partners were almost evenly distributed, such that the haptic feedback was perceived as positive. However, when it comes to different lab scenarios, designers should consider introducing limits to the amount of haptic interactions; perhaps a UI in which each partner determines the class, amount, and frequency of interactions one is comfortable with.

Effective Combination of Haptic Cues.

We provided haptic feedback with a combination of patterns, intensity, and frequency. While all of these combinations can target diverse contexts and experiences, these decisions should not be arbitrary. For example, if a pattern is considered so passive that it can be easily ignored or confused with another, instructors have to consider what modifications would be appropriate to call the attention of a participant. These settings should be altered based on students' feedback and are also dependent on the learning material.

4.8.2 Effect of ColabAR in TAR laboratories

The second question in this paper addresses how to optimize a distant laboratory such that performance and user experience improved based on our toolkit. In this paper, we analyzed qualitative, quantitative, and semi-structured interviews to understand how our toolkit had an effect in the laboratory. From our results, we observe that TAR laboratories show a promising solution to distance learning; but their efficacy is dependent on the use of multimodal feedback as outlined below.

Visual, Voice, and Vibrotactile Feedback.

Visual cues are inherent to an AR environment; thus, in a TAR laboratory, they should be leveraged to provide spatial and temporal guidance to participants (e.g., arrows, text, diagrams, etc.). However, participants reported on the importance of voice sharing alongside haptic feedback in order to clear confusion and simplify information process and transfer. This is backed by our results, in which the AR+Haptics condition resulted in increased performance, as well as a decrease in the overall time that it took participants to complete the laboratory. We also found that not aligning this multisensory feedback leads to confusion and should be avoided if possible when designing a TAR laboratory.

Role Emphasis.

The TAR laboratory designer/instructor is capable of determining whether each participant will play a specific role and what equipment each will handle. This should be leveraged to target weak spots of any participant, so as to give him/her more responsibilities that include more practice in a particular role (e.g., pipetting, handling the multimeter, etc.).

4.9 Limitations

We included 40 participants to test the initial implementation of our toolkit in a TAR laboratory environment. The subject areas we chose were *Organic Chemistry* with participants with experience of physical labs in STEM areas; and *Circuitry and Electronics* with participants without STEM background. However, given the diversity of courses in an undergraduate curriculum, we would need more testing of laboratories and equipment. A semester-long evaluation would also provide deeper insights into the adoption of the system. Finally, while we provide room for different customization options using our toolkit, we may realize that more suggested types of feedback need to be added into the library of interactions.

4.10 Conclusion

This paper introduced a toolkit to facilitate and improve collaboration in TAR laboratories, more specifically, for STEM courses. We showcase a prototype system and two user studies to demonstrate the capabilities and value of our toolkit. By adding haptics to a TAR system, we enabled students to feel awareness and empathy towards their remote partners, feel confidence and share information about the experiment, successfully navigate the physical and virtual world, and have an overall enjoyable collaborative experience. We also demonstrated that our TAR laboratory provided comparable performance results to a laboratory with physical components. Additionally, our TAR laboratory decreased students' completion time by 25%. These results are a preliminary step towards creation and integration of TAR laboratories into classroom environments. We expect that laboratories of this kind will be seen as a promising step towards more natural interactions with distance technology. Thus, designers and instructors can use these collaborative technologies, which provide useful and enjoyable learning environments.

4.11 Acknowledgments

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4.12 Authors' contributions

AV conceptualized and designed the contents for this work; participated in acquisition, analysis, and interpretation of data. ZZ worked on architecture design and conceptualization; participated in acquisition of data. ZL designed contents for this work; worked on fabrication; worked on acquisition of data. FW worked on architecture design. SC has drafted the work and substantively revised it. KR has drafted the work and substantively revised it. All authors read and approved the final manuscript.

5. CRAFTING, CODING, AND CREATIVE WRITING: REFLECTIONS ON A CASE STUDY WITH COMPUTATIONAL THINKING AND PHYSICAL COMPUTING

Figure 5.1. Overview of the STEAM activities involving coding using our Grove-Blockly platform, crafting using IoT components, and creative writing.

5.1 Introduction

Emerging trends point to researchers and K-12 educators moving towards bringing computational thinking (CT) concepts outside of the computer science (CS) classroom and towards other subjects [224]. In K-12 education, embedding CT alongside reading, writing, and arithmetic would be an important step towards providing children with comprehensive analytical abilities [225], [226]. By bridging CT and other non-CS subjects, educators can contribute towards the vision of computing as a *fundamental literacy* that can be repurposed by students throughout their lives [227]. For instance, designers, project managers, and other team members typically need to be aware of which computational solutions are available to successfully collaborate and provide alternatives and solutions to their teams [227], [228].

Currently, implementing CT concepts into a K-12 classroom is impeded by several concerns, such as teachers' experience and understanding of the content, curriculum flexibility and engagement, and budget constraints [224], [229]. Maker education, which is often associated with STEM/STEAM (Science, Technology, *(*Arts), Mathematics) subjects [230]–

[232], is credited with accelerating the integration of computing into K-12 education. This integration is often described as a learning-by-making approach in which students are highly engaged participatory in creative and interdisciplinary projects [233]–[237]. Maker education provides the benefits of combining traditional arts and crafts and digital technology in design and prototyping [235].

Our understanding of making is inspired by constructionism, an approach to learning in which the design process and the "objects-to-think-with" are–simultaneously–materials in the student's environment and internalized mental structures [238]. The combination of these materials–to build creative projects–and ideas are crucial parts of the learning process [239].

Past work on STEAM learning has primarily focused on the relationship between making and digital technologies [230]–[232]. However, constructionism positions learning as a bridge between past and new knowledge, while creating projects of contemporary relevance [240]. Thus, in order to implement CT concepts into non-CS subjects, we need a closer look at how would a curriculum that integrates both would look like. In this crossover, programming is approached with the most trepidation from arts educators out of all digital art concepts, as it is often not considered an effective expressive medium [241]. However, programming and creativity can bring about a unique, transformative process to each STEAM subject [241]–[243]. To investigate an inherently creative discipline in the context of this paper, our intended non-STEM audience was comprised of creative writers' students. Creative writing, which is referred to as open-prose or construction, based on a topic (imposed or self-selected), has the purpose of self-expression by the writer [244].

In this work, we present a case-based approach [245] to integrating how students interact with a curriculum based on block-based programming, crafting, and creative writing (Figure 5.1) at a writing-based summer camp during a week-long session. First, we began by lowering the entry barrier to programming for novice learners by implementing block-based programming [246] into our Grove-Blockly website application containing the curriculum. The learning content inside the platform also includes sample creative projects featuring Grove components [247] for physical computing (PC), which the students code in the website, and which they put together while crafting artifacts. Then, based on the projects students built upon, they construct creative writing stories which feature both the crafting project and the functionality of the PC components. In this way, we hope that the HCI community will benefit from the interdisciplinarity and different perspectives brought by non-STEM teachers and students to use STEM tools as part of their curriculum. With this work, we seek to broaden our awareness on:

a. how to better understand the writing-camp students in bridging previous (creative writing) and new (CT and PC) knowledge.

b. how to better understand non-STEM teachers in facilitating a STEAM workshop.

c. how to better understand the intersections of practices of crafting, coding, and creative writing coming together.

5.2 Related Work

5.2.1 Computational Thinking

Since its inception, CT has been considered an essential skill of the 21st century and defined as the decomposition of a difficult problem into broken pieces, by using algorithms and abstractions that can be generalized to other problems [226]. Previous work has shown that CT concepts are more likely to be internalized when combined with making and crafting [248]–[250] as opposed to programming alone [251], [252]. A functional description of the problem-solving process involving CT is the following [253], [254]: (1) understand how to solve a problem computationally; (2) organize and analyze information; (3) generate abstractions and patterns through models; (4) understand algorithms, a series of organized steps; (5) implement the most efficient solutions to achieve a goal; (6) generalize and transfer a solution to other areas. However, past research has stated that more work is needed to aid teachers in understanding CT and the development of CT concepts [255].

Algorithms are core to CT and can manage the tasks that everyone engages in, from following a simple cooking recipe to giving complex driving instructions [225]. There are some misconceptions in the understanding of algorithms as only being used to solve mathematical problems, instead of their applicability in other subjects, which is why instructors can benefit by introducing them to their students using examples of tasks from their daily lives [256].

For instance, children can become acquainted with the concept of algorithms by following a lemonade recipe, while older students can follow the steps in a laboratory. Understanding an algorithm as a series of steps is the basis for students to implement solutions to problems in computer programs [253]. Similarly, it is important for students to understand the CT concept of abstraction by creating physical models of abstract concepts [256]. For example, students can understand how an abstract concept like electricity by building a house made of paper, placing the circuits inside it, and seeing it light up.

Curricular activities involving programming and design have been typically used as an iterative exploration of CT concepts [253]. These curricular activities aimed at younger students typically involve block-based programming, which is targeted at novices to build computer programs by snapping together graphical blocks to assemble algorithms [246]. Popular graphical programming interfaces include Scratch, Alice, Game Maker, Kodu, Greenfoot [257]. A combination of programming and physical-making activities has shown an improvement in engagement and learning outcomes in key competencies involving CT concepts (e.g., loops, conditionals, and events) and practices (e.g., remixing, testing, and debugging) [258], [259]. While these curricular activities have been aimed at STEM disciplines, less attention has been given to CT in non-CS subjects. Also, given that these non-CS subjects would likely be taught by non-CS teachers, then the curriculum has to be carefully crafted and be: (a) sufficiently constrained in length and scope, which allows the non-STEM teacher has the opportunity to be comfortable with the content and be able to help students with problem-solving and debugging; (b) creative and flexible in hands-on projects, so that it can keep students engaged and be embedded into the non-CS subject.

5.2.2 Constructionism, Physical Computing, and Making

This work is grounded by *constructionism*, an approach to learning by which knowledge is better acquired resulting from experiences with "objects-to-think-with" as a symbiotic relationship between material objects and internalized mental structures [239], [260]. This understanding of material objects underlies the idea that abstract concepts, including mental structures, can turn concrete through design [242]. In this process, the student is not a pas-

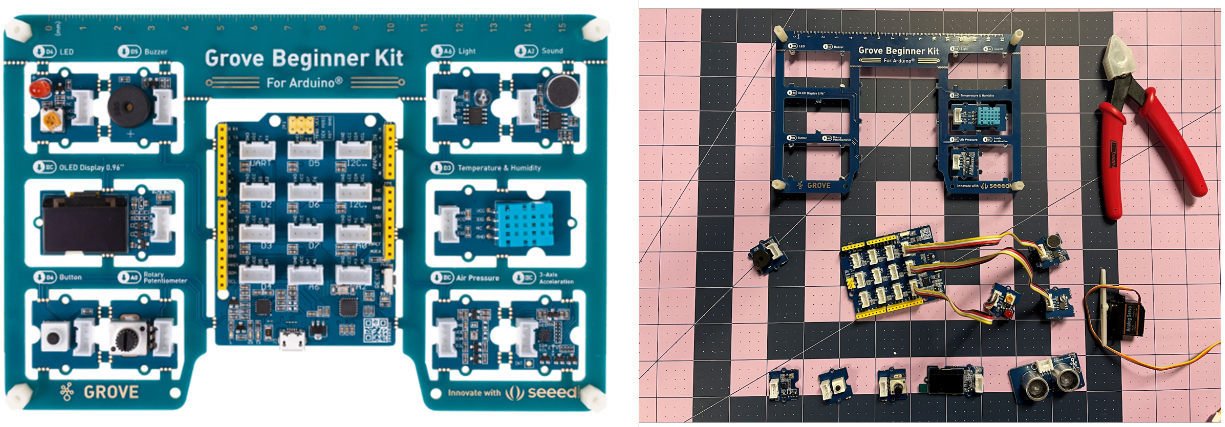


Figure 5.2. *Left*: Grove Beginner Kit for Arduino. *Right*: Separated IoT components from Grove board.

sive recipient of the knowledge, but rather an active learner [239]. In effect, constructionism positions learning as an approach to reconcile previous and new knowledge, while working on projects that are meaningful to the children [240]. Constructionism demonstrates the effectiveness of learning by making, but the creation of these artifacts can also include digital technologies [261].

Making with digital technologies, which typically relies on programming, can support meaningful design experiences based on constructionism and learning activities with children [261]. These programming activities have demonstrated an improvement in CT, problem-solving, higher-order thinking, and collaboration skills [253], [262]. Block-based programming (e.g., Scratch) has the advantage of snapping blocks of different shapes together only if these blocks make a logical sequence [263]. This lowers the entry barrier for novices and provides immediate feedback to students [264]. Constructionism-based coding activities, which typically involve block-based programming, are capable of providing a useful learning environment from which students can derive exploratory and meaningful experiences [265].

Making in the physical world has had the advantage of a proliferation of user-friendly PC boards and components that have been used regularly for learning activities. For reference, [224] provides a detailed table that categorizes the most relevant and commercially available boards. We chose the Grove (Figure 5.2), a beginner-friendly Arduino-adapted kit that connected the components to the main board with plug-and-play cables [247]. This kit allows for the increasing complexity of projects and making use of multiple sensors for different contexts.

The components of this kit for PC represent the objects-to-think-with to be manipulated and used for making by the children. These objects provide valuable opportunities to study moments of engagement with the objects and observe learning as students connect ideas and materials [242]. Further research is needed to understand how these objects in PC are considered mediators between students and new knowledge.

5.2.3 Challenges with STEAM Practices

The purpose of including the Arts into STEM education is that previous work supports that an arts education can foster students' creativity, critical thinking, and communication skills [243], [266], [267]. Additionally, a rich arts education can improve spatial reasoning and abstract thinking that is connected with CT [268]–[270]. However, STEM educators have struggled to introduce arts into a STEM curricula for the purpose of fostering creativity and engagement [268]–[270]. Meanwhile, art educators have been introducing media arts including developing crafts, creative writing, exploring expression through building, making, observing reflecting, and interacting with materials [271]. These creative methods in the classroom are developed by teachers' guidance and implementation of the curriculum and not only by the type of activity [243], [272]. This implementation of the learning material by the instructors relies on their pre-conceptions about creativity and the process to teach for creative outcomes [273]. Among the misconceptions regarding STEAM education, a common one is that the arts are concerned primarily on the completed product, rather than the close observation of the learning process and how students came to think, plan, create or perform their creative work [274], [275]. Thus, we need to further investigate the learning process involving STEAM education, to understanding how the creative process leads to learning new concepts.

In its current form, the implementation of a STEAM curriculum is complicated by the pedagogical methods of non-STEM teachers, who often feel concern about delivering technical knowledge to students [243], [276]. Moreover, teachers find it difficult to teach content outside their academic qualifications, typically preferring to leave STEM teaching to instructors in a STEM discipline. We have to carefully understand how to craft a curriculum that non-STEM teachers may want to bring into the classroom, understanding how to handle materials or code.

5.3 Overview of Grove-Blockly

We implemented a visual programming environment as a web application built on top of HTML, Javascript, and CCS. Users are able to drag and drop blocks, which are generated

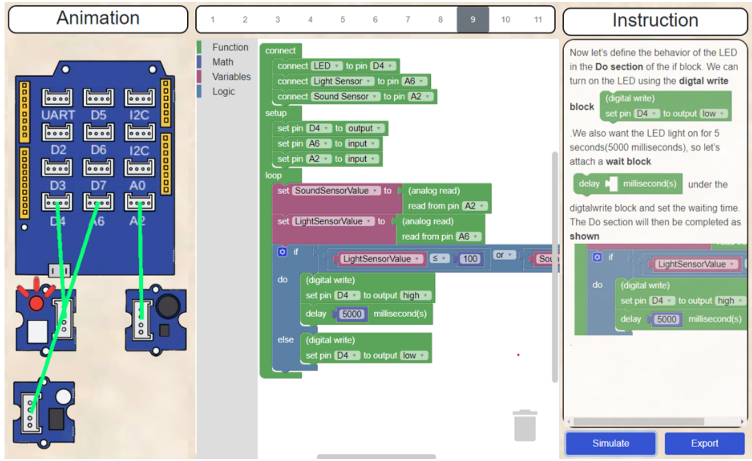


Figure 5.3. *Left*: Animation panel for visualizing and debugging. *Middle*: Workspace with the blocks code. *Right*: Instruction panel which introduces concepts and presents detailed instructions.

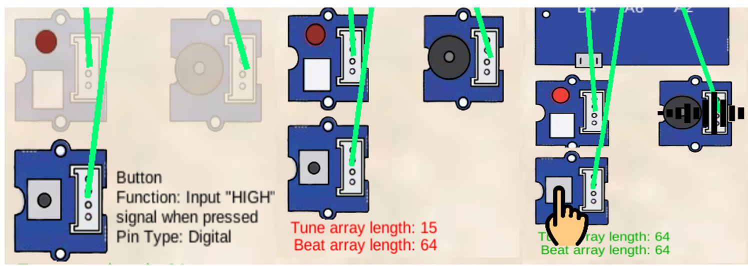


Figure 5.4. *Left*: Example of visualization of IoT functionality. *Middle*: Example of visual debugging of arrays length. *Right*: Example of visual output of the blocks code.

using Blockly, a client-side Javascript library to create block-based code construction. The visualizations for code debugging are created using Unity 3D for web applications. The code which can be exported is in Arduino programming language. The website is divided into three sections:

Animation: This section allows users to visualize the relationship between the blocks and the IoT components. In Figure 5.3 (left), this project shows the main board as a representation of Grove, an adapted plug-and-play board adapted from the Arduino Uno, and the three components shown to represent an LED, a sound sensor, and a light sensor. Since the blocks at the center of the workspace connect LED to pin D4, light sensor to pin A6, and sound sensor to pin A2, then the Animation panel is displaying the connection of the IoTs with the green line towards the board. If the user does not connect the IoTs in the blocks, then the green line is not shown. Likewise, other debugging visualizations are available through the Animation panel. In Figure 5.4 (left), we observe that details of each IoT component (e.g., functionality, pin type) are provided when the user hovers over it. This area also provides other information on the errors found in blocks, in figure 5.4 (center), we can observe that the section provides a message in red informing that the arrays are missing values. Similarly, once the Simulation button is pressed and if the code is correct, then this section runs a visualization that shows users how the IoTs have to be working in the real world. In the case of Figure 5.4 (right), it shows that if the user presses the pushbutton, then the LED starts blinking and the buzzer starts sounding beats. *Workspace:* Figure 5.3 (middle) shows the area in which students can code using the blocks. *Instructions:* Figure 5.3 (right) provides each of the instructions necessary to complete an exercise. Each step (figure 5.3, center top) contains the description of a process, introduces or highlights a concept, or gives a hint to understand how to change the blocks. Sometimes, the steps are accompanied by an instructional video.

5.4 Nexus Theory and Content Design

Combining new technologies into arts education brings new opportunities for exploring interdisciplinarity that allows researchers to participate in modifying form and environment [241]. Nexus theory proposes that when different nexuses converge, conflicts and slippages among their disparate expectations have the potential to disrupt previously stagnated practices that have been used in a discipline [277]. These practices meant to converge disciplines have to be engineered in a way that the sum of the whole becomes greater than the parts. This is why the investigation of digital and physical tools and the structuring of subject matter is central to the questions of STEAM interdisciplinary learning. According to Kafai and Burke [278], "working across different domains – crafting, engineering, and computing – underscores the importance of seeing how concepts cross a range of media and conditions" (p.101). Moreover, these experiences can be inviting to users simply walking into a space, without the need for any previous technical knowledge, and these cumulative hands-on opportunities are critical and inclusive in building knowledge and understanding of CT and PC concepts over time. With the purpose of designing learning content, we present the

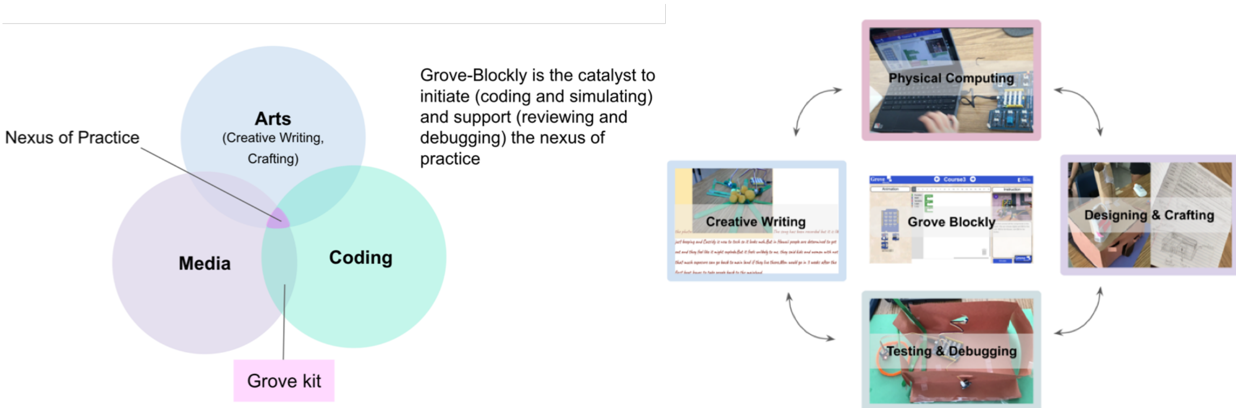


Figure 5.5. Overview of our nexus of practice, in which Grove-Blockly is the catalyst to initiate (coding and simulating) and support (reviewing and debugging) this process. The Grove kit sits at the intersection of coding and media ("objects-to-think-with"). In turn, these materials provoke students's participation in the arts through the crafting of their artifacts and creative writing of their stories.

Grove-Blockly nexus (Figure 5.5), consisting of three intersecting domains of coding, media, arts. We introduce Grove-Blockly as the catalyst to initiate (coding and simulating) and support (reviewing and debugging) the nexus of practice due to the features we described from the website application. Grove-Blockly as part of the digital media that children interact with, is supposed to be the bridge between the physical and virtual world. Thus, the presence of the virtual version of the Grove board and several compatible components, alongside the simulations and connections made through the code blocks, enables learners to concretize that which was previously an abstract understanding of computer programming. In the context of this paper, we investigate how may we get creative writing teachers and students interested in STEAM subjects through making (i.e., through the design and building of technical artifacts). For example, in bringing together theory and form, students can move from their existing proficiency (e.g., a story built around their favorite song) to a digital and physical artifact (e.g., programming, designing, and building a music box).

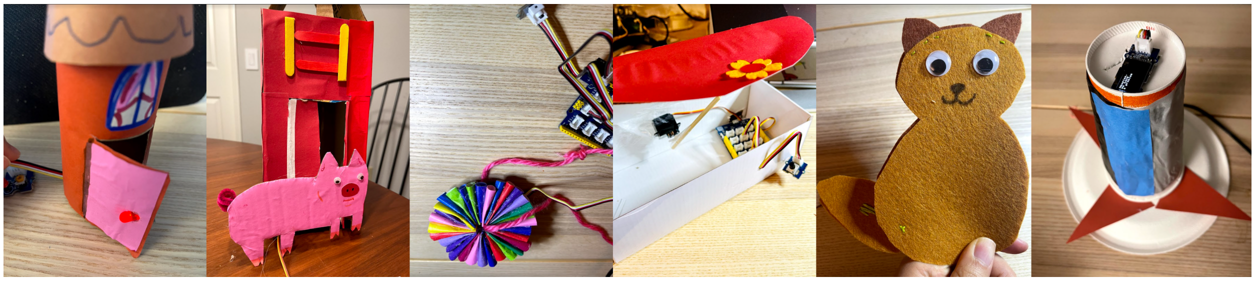


Figure 5.6. *Left to Right*: Smart House, Old McDonald Had a Farm, Musical Necklace, Treasure Chest, Robot Pet Wags its Tail, Spaceship.

The way children can approach the Grove kit as media and code, to be uploaded to the board, has to connect to students's existing passions. For instance, the creative writing students are proficient at writing, organizing, and narrating stories. In this study, we leverage the initial idea of objects-to-think-with to have students imagine which "objects" can be used to trigger a premise for them. Grove kit has sensors and actuators that can take user input (e.g., a pushbutton) or environment input (e.g., light sensor) as triggers and provide different output (e.g., LED on/off). Then, we can think of some artifacts that can be relatable to students: a house, a pet, a song, a piece of jewelry, an artifact representing a dream job, a coffee shop, an item of clothing, etc. With some of these artifacts in mind, we can build a bridge with the students's interests in two ways: the students can think of a story they can write on the artifact of their choice; the students can begin programming and designing with their artifact in mind. For example, if building a house and using a motion sensor and an LED, where can the motion sensor and the LED be placed in the house structure? What does the design of the house look like? Is the design informed by the storyline decision? What functions and parameters are used in the code? Is the writing influenced by the output of the code?

5.4.1 List of Projects

Using this nexus of practice, we added a pre-lab section and six STEAM projects to the Grove-Blockly website. Before students were introduced to the projects, in order to introduce them to CT and PC concepts, we presented the following exercises: **(Ex. A)** Make the LED blink; **(Ex. B)** Use the potentiometer to control and display numerical value on the OLED; **(Ex. C)** Use the potentiometer to control the brightness of the LED.

We present six projects that we prepared for our lesson plan (Figure 5.6): **(1) Smart House**: Design and build a house that turns on the LED when the light sensor detects darkness or when the sound sensor detects a loud noise (e.g., knocking or clapping); **(2) Old McDonald Had a Farm**: Design and build a farm and a farm animal of your choice, then use the potentiometer to control the servo motor and create movement from the animal; **(3) Musical Necklace**: Design and build a necklace, then once the pushbutton is pressed, the buzzer is made to play the tune of a song of your choice and alternate the LED blinking with the beats; **(4) Treasure Chest**: Design and build a treasure chest, then using the potentiometer, control the servo and create an open or close motion from the lid of the treasure chest; **(5) Robot Pet**: Design and build a favorite pet, then using the ultrasonic distance sensor to detect owner's proximity, program the servo motor to make the pet wag its tail; **(6) Space Ship**: Design and build a space ship. Using the 3-axis accelerometer, which alerts when the spaceship has "taken off" (i.e., upward movement is detected).

5.5 Evaluation

5.5.1 Setting, Participants, and Workshop

We conducted the study at the charter middle school in Southern California, USA, during a writing-based summer camp as part of a NWP (National Writing Project) program with their students. We provided the learning curriculum that educators easily adapted with the integration of our Grove-Blockly visual programming platform, Grove board, and crafting kits. The study took place during the first week of the workshop that ran 2.5 hours each day. Three researchers were present and measured learning gains and examined how students participated in these making projects. The researchers helped the workshop in answering any questions the children may have and also conducted pre-/post-tests, took videos, pictures, and performed semi-structured interviews with the students. 18 students participated in the workshop between ages 11 to 13 (6th to 8th grades). From the total number of 18 students, only 16 students were able to take pre-/post-tests (female=6). 3 out of 16 participants self-identified as White, and the others identified as either Black, Hispanic, or Mixed Race.

The main instructor had teaching experience of over 9 years. She teaches all subjects for 5th graders. She reported no prior experience with making, IoT kits or designing project-based learning. She also reported no prior experience with programming with a physical computing kit (sensors and actuators).

5.5.2 Workshop

First, students were introduced to Grove kit and basic hardware concepts, such as inputs, outputs, and sensors. The lesson plans were scaffolded with three exercises in Grove-Blockly website. During the computing activity, the teacher explained the CT concepts (e.g., loops, conditional logic, and variables) with real-life examples that connected with the blocks which students used in the exercises. After students completed all three exercises, they were able to follow the step-by-step instructions in Grove-Blockly to finish the coding for a project that allowed them to create an artifact of their choice. Second, students spent most of their time in the workshop on designing and crafting their projects. During designing and crafting, students were able to draft and create their prototypes; meanwhile, the creative writing was developed and evolved in this process. Third, students tested and debugged their design by putting the Grove components and crafts together. This process is entirely reciprocal in that students can go back and forth as needed to craft and test their prototypes. Finally, students shared their work and initial thoughts of the story as well as their reflection on Padlet.com.

5.5.3 Data Sources and Analysis

We designed pre-post test questionnaires to examine the learning gain of three criteria: 1) computational thinking (CT), 2) physical computing (PC), and 3) students' acknowledgement of the relationship between these two concepts (CT PC).

At the beginning and the end of the one-week workshop, we handed out paper-based pre- and post-tests to assess the three concepts: CT, PC, and CT & PC. Students were provided

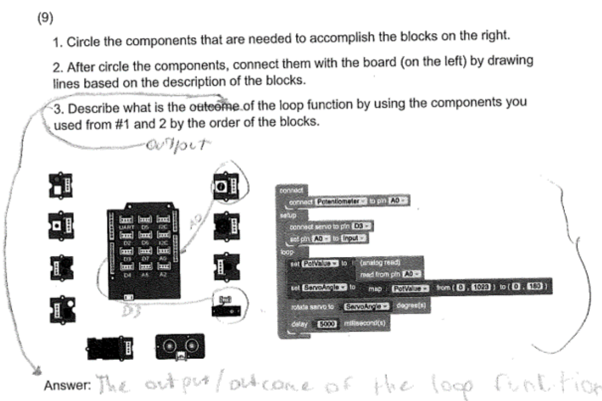


Figure 5.7. Sample Q&A written by a students (Clara, pseudonym)–cropped: *"The output/outcome of the loop function by using the components I used from 1 and in order of the blocks/code placed in order is first the potentiometer will need to be connected to pin A0, then needs to connect servo to pin D3. Next it will send pin to A0 and to input. So it loops over would set the PotValue to analog read, read from pin A0. Set ServoAngle to map PotValue from 0, 1023 to 0, 180, rotate servo to servo angle degrees(s), delay 5000 milliseconds in the end. Once you turn the potentiometer it will make the motor turn on."*

images with a set of coding to explain the result (outcome) of the block-based codes as well as to simulate the functions and draw lines across the components to accomplish the tasks. In Figure 5.7, we showcase a sample question and answer from a students (Clara, pseudonym) at the post-test stage. We then developed coding schemes to examine students' competencies in programming and IoT concepts from the pre-/post-tests' answers. We calculated Cohen's kappa to obtain the inter-rater reliability of the coding scheme between two graders: k =0.73. The two researchers took a path on scoring based on a previously decided upon coding scheme. Finally, building on the coding results, a paired sample t-test and one-way ANOVA were applied to examine the statistical differences and learning gains between pre-and post-tests.

5.5.4 Results

In the workshop, we found that arts integration promoted e-crafting with IoT devices that lead to artistic expression (creative writing) into STEAM engagement. The results indicate that all students improved on the concepts of CT, physical computing (PC), and CT and

Table 5.1. Paired Sample T-Test Results from the Pre/Post-Test

Key Competencies	Gain				Pre-test		Post-test	
	M	SD	t	P	M	SD	M	SD
Total	10.69	4.51	**9.47	<.001	2.75	2.98	13.44	3.76
Computational Thinking (CT) Concepts (e.g., algorithm building, loops, conditional logic, functions)	2.06	2.14	*3.85	.002	1.00	1.32	3.06	1.73
Physical Computing (PC) IoT components and concepts (e.g., setup, connect, sensors, actuators, inputs, outputs)	3.31	1.54	**8.62	<.001	.88	1.09	4.19	.98
CT & PC Connection between IoT components with the CT concepts in the Blockly code	5.31	2.09	**10.17	<.001	.88	1.26	6.19	1.8

PC from pre- to post-tests (see Table 5.1). The preliminary results from pre-test (M = 2.75, SD =2.98) and post-tests (M = 13.44, SD = 3.76) showed a significant improvement for students on understanding the connection between IoT components with the CT concepts in the Blockly code (M =5.31, SD = 2.09), t = 10.17, $p < .001$. The findings suggest that all students' key competencies in both CT and PC improved from the workshop. Particularly, students showed significant improvement on understanding the connection between CT and PC (IoT components).

5.6 Findings

Overall, our hands-on workshops that combined crafting, coding, and creative writing were effective in enhancing children's understanding of coding and IoT components. The teacher was enthusiastic about taking on a new curriculum and felt confident her students had successfully internalized the new content. However, she was anxious to engage and expand on content and projects outside what was provided by the website. In some ways, we anticipated that teachers would feel reluctant to take on concepts they had never worked on before, given the novelty and scope of the projects. In consequence, we expect that our website will need continued growth to add on more instructions and content. We expand on the expected outcomes of our workshops:

5.6.1 Better understanding of the writing-camp students in bridging previous (creative writing) and new (CT and PC) knowledge.

Computational Thinking Meets Creative Writing

In the creative writing section, students incorporated the different coding elements of their project into the story. Carter wrote that the family in his story “ran off and the power fell off” during a fire (*Inspiration from Smart-House project functionality*). Stella wrote about a magic music box given by her grandmother before her passing away and left with the message that it would "start the song if she would just press the button” (*Inspiration from Musical Necklace project functionality*). As Stella’s story progresses she discovers that her music box also “glows” and takes her through a portal, similar to that of “Alice in Wonderland”.

Ryan wrote about a team of “astronauts losing and eventually finding a rocket from NASA” (*Inspiration from Spaceship project functionality*). During the story, the rocket falls and is lost by the crew. Then, as it throws them off, the physical rocket shows “Houston, we’ve got a problem!”. After the rocket is found again, the crew gets it to take off with the display message: “Hasta la vista, baby”. Mia wrote about a cursed vampiric Peppa Pig living on a big hill (*Inspiration from Old McDonald had a Farm project functionality*). As another character approaches Peppa, he proceeds to swiftly disappear in the basement while he “investigates the house".

Debugging and Creative Writing

The children first approached the creative writing activity by preparing a plot diagram with the following steps: 1) exposition, 2) conflict, 3) rising action, 4) climax, 5) falling action, 6) resolution. In a similar way, teachers encouraged students to approach problem-solving across coding, crafting, and writing activities. On day 2 of the workshop, the teacher instructed students to create an algorithm (i.e., a series of steps) for the perfect lemonade recipe. The teacher provided the ingredients and served as a "judge" to determine if the students had gotten the correct algorithm.

Likewise, it was important to contextualize CT concepts within the process of creative writing, with which they were already familiar. For the rest of day 2, they spent the time fixing several bugs in exercises given to them in printed worksheets. In this context, framing debugging in Grove-Blockly as a plot diagram was helpful because students were used to thinking along these lines.

In the exercises for Day 2, students completed several activities that included generating pseudocode, reading and understanding code, and fixing bugs in the blocks. Students received these activities positively and commented that they were helpful to understand coding. The activities included: match blocks of code with images of the physical components, understanding input/output, analog/digital concepts, functionality and order of the blocks, writing pseudocode of an algorithm to collect data from a sensor, and trigger output from an actuator.

Strategic Design

As for the construction decisions on Day 4, at this point students had already decided on which artifact they would incorporate into their writing. Thus, students had to make several decisions on the design process of their physical artifact: How to position the components given the length of their cables connecting them to the Grove board? How to position the components to be fixed or stable inside their construction? How to fit their components in an effective way to fit their narrative and purpose? For example, in the case of the Smart House project, students had to determine how to place the light sensor so that the roof of the house would not permanently cover it, thus keeping the LED permanently on. Then, students created windows, balconies, removable roofs, to complete their projects as planned. In doing so, they reinforced their understanding of the functionality of the sensors.

Students also had the chance to explore changing the parameters (e.g., LightSensorValue < 100 to detect darkness), which were the raw analog readings from the sensors, and used to create conditional statements by choosing thresholds to trigger an action (e.g., light up the LED) and changing the time in the delay function to wait for the action to end. These explorations reinforced the concepts of conditionals, functions, logic, etc.

5.6.2 Better understanding of non-STEM teachers in facilitating a STEAM workshop.

Teachers' Perspective

We had a series of semi-formal interviews with Jenna (pseudonym) after each day at the camp and we also provided a questionnaire to understand her perceptions about the workshops. She praised how *"the hands on aspect was great and the program was easy to follow"*. The most important aspect for the teacher was to have an available website that clearly delineated the learning material that would span the coding, IoTs, and making. However, the teacher felt that the website can work well when including an in-person instructor.

The teacher mentioned that the website was useful for *"understanding the foundational information of how programming works."* However, she *"had to ask lots of questions and wouldn't have been able to do it on [her] own."* In the latter statement, she is referring to the 2 2-hour sessions we had prior to the summer camp to walk through and learn the IoT-coding part. The three researchers, alongside the teacher, co-designed introductory slides to use as multimedia tools during the week. The teacher found these slides to be helpful as the most *"challenging during the workshop was honestly the perception of teaching students how to code when I barely understood much [of the content] at beginning of the program. I found that the introductory slides that explained how to code and the different aspects of the workshop were really well done and explained it very clearly."* Her favorite part of the camp was seeing her students getting their code to work: *"Having student have that aha moment of fixing a line of code and having it work or having an issue with their project and being able to fix it themselves."*

The teacher mentioned that she would have preferred to give more time to the crafting section and thought she did not give *"enough time to create the pieces that went with the codes."* She also pointed out that *"technology and coding a skill within itself that needs its space and time in the classroom."* She highly rated the performance of her students during the summer camp and the website and content. However, she reported apprehension at deviating from the curriculum, meaning that she would only feel comfortable repeating the lesson plan that was provided.

Students' Perspective

In the informal discussion during the last day of the summer camp, students voiced their satisfaction with what they had learned. For instance, Carter reported that he had *"enjoyed [the activities] much more than he expected"* and that once he started he *"wanted to keep going"*.

While only a few students had previous experience with Scratch, those students mentioned that the hands-on aspect of IoTs made the relationship of sensors-code easier to understand. Clara said: *"I've done something a little bit similar to this but it's just on the computer that we're just doing the coding... It was a little bit hard on me at first but now all of sudden when I understand [the sensors] as it goes on."* Dylan also concluded that the back and forth and struggle helped him learn more: *"I feel like I know a little bit more, because of all the frustration and the situation that went through it."*

Matt expressed his satisfaction at completing his spaceship and thought his next steps would be to continue: *"I'm going to... going to use this code and modify it now. I'm going to use it to test other code. I hope I don't literally fry this [board]. [I'm] not much of a modifier... but I want to try."* Stella also mentioned she had been working on another project from the website at home and she had been *"super happy the buzzer was working"*.

Students used Padlet to comment on their projects and how they felt about the options given by the prompts. An important trait of using a prompt as a spaceship or a smart home as evocative artifacts is how connected the students were to the entire design process. Several rounds of prototyping or of modifying their structures were voluntary performances by the student. The students spent their time building their dream house or a replica of the first toy they ever built, which provided a sense of ownership and involvement that surpassed their own expectations as per their comments in Padlet. This kind of introspection should be encouraged as it appears to be a central part of the learning process.

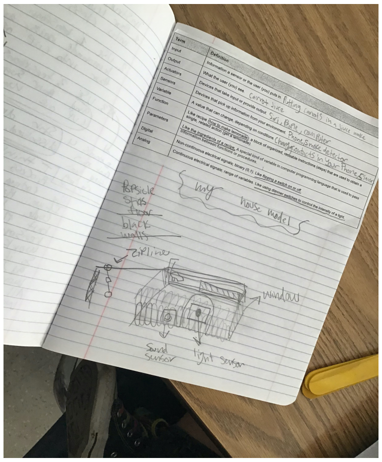
5.6.3 Better understanding of the intersections of practices of crafting, coding, and creative writing coming together.

Nexus Practices coming together

During the 5-day workshop, students were able to create a digital craft object (e.g., smart house) by incorporating the components – LED, sound sensor, and light sensor for them to think with and reflect on. We applied nexus theory to develop project activities and expected outcomes. Due to the novelty of programming, the emphasis in support and time was placed in *media* and *coding*. In the discussion and post-questionnaires the instructor and the students regretted not dedicating enough time to the crafting, which everyone felt was the most fun. However, given the learning gains shown in the post-test scores, focus on *media* and *coding* may be a fair compromise. The *media* (IoTs) were comprised of plug-and-play set of sensors and actuators. While the variability of the components enabled many combinations of IoT devices, the shape, length, wiring, provided constraints for the *arts* (crafting). The design of the artifacts had to be repeatedly prototyped by the students so that the components would support and fit in balance between form and function. While this process was repetitive, it facilitated critical thinking and creativity in students. Incorporating the *arts* (creative writing and crafting) means meeting the students at their personal interests. During the design process, the researchers were asking the students about their design strategy and prototyping. Although most of the students were proficient in writing and generally good at expressing themselves verbally, a few of the children struggled to communicate their intentions during the design. On a positive note, we observed that the students who were less communicative were talented at expressing themselves through design. In turn, once they had completed their design, they were also more communicative through the online platform, i.e., Padlet.

Vignette 1 (Table 5.2) below demonstrates an example from the student, Emma, to illustrate the development of the nexus of practice through designing and crafting. In lines

Table 5.2. Vignette 1: Time: The third day of the workshop (Designing Crafting)



1. **Emma**: And then inside, like right where the door is going to
2. have a sound sensor, I mean, a light sensor. So that when it
3. lights up, it slides up the whole room in the middle of the room
4. and then behind the paper, right next to it is the sound sensor.
5. So if you clap outside the door (sound sensor), you can see the
6. light pop up (LED). And then this whole side of the wall is
7. going to be windows. And then there's going to be a zip line
8. and pool, chairs.
9. **Researcher**: Oh pool, fancy, so it's like a rooftop pool.
10. **Emma**: Yeah. I'm going to have wood floors, fancy wood floors
11. with popsicle sticks. I think I might put furniture inside, but
12. you can't really see it.
13. **Researcher**: Maybe you can put it (light sensor) by the window.
14. **Emma**: Oh yeah, that's the whole thing. I'm really excited.

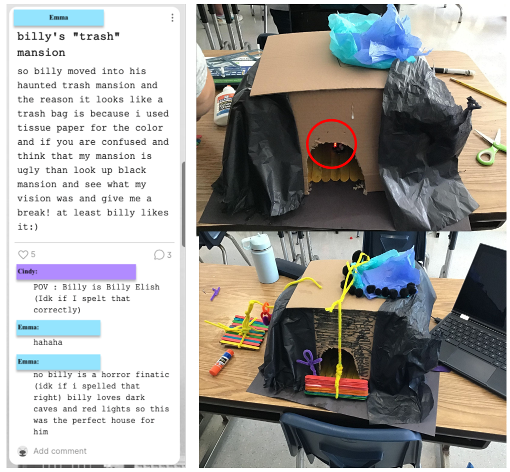


Figure 5.8. *Left*: Emma's comments and interactions in Padlet regarding her artifact. *Right-Top*: Testing the prototype with Grove components. *Right-Bottom*: Final product-Smart House like Billy's Trash Mansion

1-8, Emma explained the design of her house and how she incorporated the IoT components into the design (LED, sounds sensor). Additionally, she took into account the spatial element to place the components (i.e., placing the sound sensor outside the door) to simulate the use in real-life conditions. Moreover, from lines 9 to 12, the researcher showed interest in the design and Emma elaborated on the design for the interior space of the house. Lines 13-14, a discussion about the change of the light sensor location in the house which is shown in Table 5.2. The vignette shows how the IoT components were integrated into the design, craft, and objects and demonstrates the nexus of practice among arts, coding, and media. After testing and debugging, students shared their reflections and initial comments on the story in Padlet.com. Emma's work shows an exemplary work for how students integrated the Grove components into their prototype design and story. Emma referred the house she built as "Billy's Trash Mansion", in which she created a character, Billy, and described the design and look of the house (see Figure 5.8). Following the peer's comment, Emma further illustrated the character and how the red LED light connect with Billy's characteristics. The narrative started coming out from the design itself and vice versa. Emma then expanded on her story in a Google doc in a Drive folder shared with the teacher and the rest of the class.

5.7 Discussion

We centered on nexus theory of practices to design the learning content spanning interdisciplinarity between arts, coding, and media [241]. In this way, we were able to leverage our Grove-Blockly platform to teach CT concepts and to be catalysis of a lesson plan involving PC, designing and crafting, testing and debugging, and creative writing. Our findings indicated that our approach successfully managed to reconcile old (creative writing) and new (CT and PC) knowledge. The improvement in learning gains stems from emphasizing strategies of the lesson plan (i.e., more time building diagrams, debugging, and programming) and compromising other parts (i.e., less time for crafting).

Structuring the lesson plan to support CT and PC. The *making* process has to start with the pre-production and planning of possible projects, designs, models, and ideas. **Identifying** the opportunity by evaluating how we can bring creative writing teachers and students to be interested in STEM. The case of creative writing is particularly interesting because students take much inspiration from "pop-culture". For instance, the students drew inspiration from games such as Minecraft, Roblox, Among Us, to build their artifacts, from anime such as Attack on Titan, from music artists. STEAM educators should encourage this kind of cross-over which enables building artifacts from meaningful experiences or interests. This is a useful way to bring the students's universe into STEAM. This is an interesting starting point to decide the theme of their work, which eventually becomes a story, a design, an artifact, a maker project. **Connecting** what they know with what they are learning is central to softly introduce concepts in an informal setting. For instance, algorithmic thinking can be framed as a series of steps, not much different from the plot diagrams creative writing students tend to follow to put together their stories. **Exploring** the making process as iterative involving models and prototypes. We begin with the Grove-Blockly platform and enabling the functionality of the IoTs by putting the blocks in order. Then, preparing the IoT physical components for testing and seeing if the block codes and parameters were useful to the ends of the project. The designing and crafting goes back and forth and is the product of decision-making and planning. However, most of these design decisions were made by the students after periods of trial and error, i.e., testing and debugging, their structures and artifacts. Once their artifacts were crafted and tested for functionality, the students should get plenty of time to write about their projects with the story they had in mind. **Highlighting** is giving the students the opportunity to share, comment, and encourage each other on an online platform. This is a central step for students to showcase to peers what they build, what they wrote, what they liked, what challenged them. This is also important for community building and facilitating connections between students. **Reflecting** on what was learned, which can be measured through pre-/post-tasks to validate the effectiveness of the lessons, but also to get students's impressions on the STEAM activities.

Support mechanisms for STEAM content in non-STEM classrooms. Our findings shown that the teacher felt satisfied with her performance and also felt confident that her students had internalized the new concepts. However, she reported feeling insecure about taking the lesson plan further and making new projects or assignments. This anxiety is understandable given that IoT-programming is not a subject matter of expertise for non-STEM teachers. The teacher did report enjoying the activity, even if she had to be trained and ask questions to the researchers. Additionally, she reported that useful media we provided were the slides we co-designed after the first day of the summer-camp. A mechanism to support the teacher could be to continue creating templates and instructions that other non-STEM (e.g., literature, chemistry, geography subjects) teachers can share with each other. In doing so, non-STEM teacher could have extensive content to teach their students and would bypass the anxiety of creating relatively unexplored content from scratch.

During the workshop, the most useful feature in the platform was the graphical debugging interface (Animation panel) that provides mental models for non-STEM students that simplify and familiarize them with the trouble-shooting process in the coding (i.e., abstract concepts) and in relation to the physical components (i.e., tangible pieces). This animations are a practical way to showcase to students abstract concepts in the virtual platform before they get to test them with the physical IoTs. Debugging and testing of arrays, functions, loops, conditionals can be understood through visualizations or cues that provide hints on the errors. For example, if an LED stays on instead of blinking, then it may mean the blocks are missing a LOW setting. If the opposite is true, then the blocks may be missing a delay() function. The website was able to these errors and display a message. The teacher made sure to indicate that any feature that helped students spot their error (e.g., syntax, missing blocks, missing connections) is the most valuable time-saver that enables to complete the work. The design and prototype stages were crucial for the students to acquire mental models of IoT-programming. However, both the teacher and the students reported that they would have preferred an extra day for their crafting. Students did not get to the design/crafting process until the fourth day of the camp. This delay was primarily due to prioritizing the IoT-programming learning; but also due to students exploring different materials (e.g., cardboard, paper, color pencils, acrylic paint) to build their artifacts. The teacher suggested that next time, she would prefer to start the design by providing the students with a set of materials (e.g., 4 cardboard squares, color paper) as to speed up this process.

5.8 Conclusion

In this paper, we validate the nexus theory of practices to examine the learning gains and slippages across media, computing, and creative writing. We presented the Grove-Blockly platform as the catalyst to initiate (coding and simulating) and support (reviewing and debugging) the nexus of practices of these interdisciplinary subjects. Building on the constructionist approach, students reflected the processes of making, crafting, and programming in their creative writing. Students demonstrated their understanding of the IoT components not only through their assessment, but also through their artifacts. In terms of learning assessment, students showed a total improvement of up to 79.5% in learning gains from key competencies in computational thinking and physical computing concepts. Finally, students created e-crafting projects which supported the development of stories and vice versa. The power of the arts-based maker activities, with the integration of new methods such as creative writing, introduces promising ways to design high-quality STEM learning programs towards computing and engineering education open to the arts.

5.9 Selection and Participation of Children

To have access to participants, we worked with a school affiliated to the National Writing Project (NWP). We contacted the charter school and collected contact information from administrators and some of their teachers who expressed an interest in STEAM workshops. The children had already signed up for a two-week summer writing camp, but they were informed that the first week would include working with circuits. Prior to the study, parents of the children were provided with the study description sheers explaining the procedure and goals of the study, the data that would be collected, analyzed, and presented. All children whose data is presented had a written parental consent form. At the start of the week, the children were provided with the same written information and had an informal discussion to explain the study and give them the opportunity to ask questions.

6. TOWARDS MODELING OF HUMAN (MICRO)SKILLING FOR ELECTRICAL CIRCUITRY USING AUGMENTED REALITY APPLICATIONS

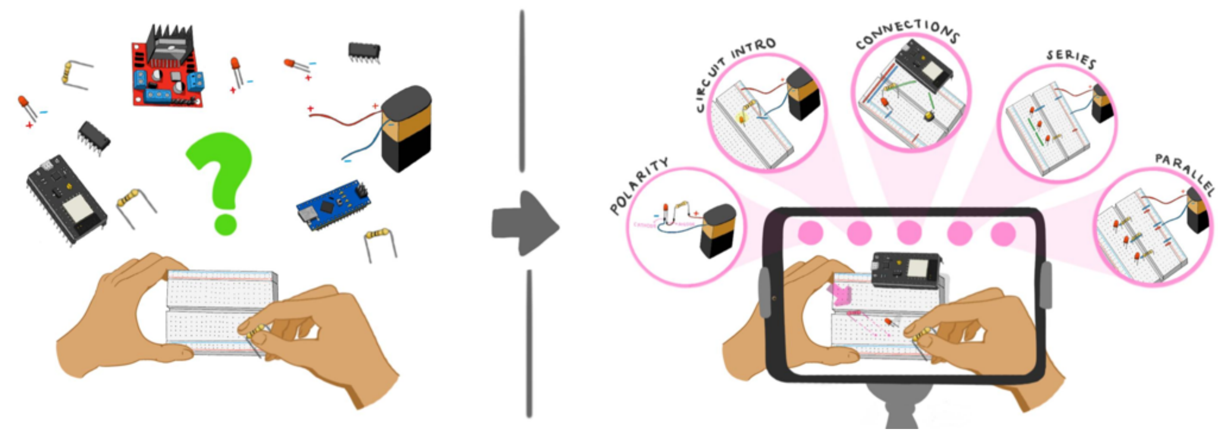


Figure 6.1. Overview of our model to provide a user with basic mastery of electrical circuitry. (Left) Electrical circuitry as a wide body of knowledge with multiple concepts and electrical components, even at the basic level. (Right) We break down electrical circuitry into fundamentals or microskills–smallest segmentation of this knowledge–which are delivered by AR (phone-based), allow the user to perform a variety of tasks that are conducive to the acquisition of the skill.

This chapter is presenting work published at the International Journal of Educational Technology in Higher Education [279].

In this work, in order to systematize the process of breaking down, aligning, and improving the AR content, we propose the use of Q-matrix theory, a cognitive assessment approach which evaluates the associations between questions/steps in a task and the microskills–smallest segmentation of knowledge–required to complete it [280], [281]. Q-matrix theory has been utilized previously for cognitive assessment in multimedia learning, but not in the context of developing an AR curricula [282]–[284].

This work investigates the use of Q-matrix theory as a design framework to develop an AR-based curriculum (Fig. 6.1). We focused on a young-adult population (18-34 years) without any prior knowledge on the subject area of electrical circuitry. The tasks chosen for the user studies involve different procedures; however, the microskills required to complete them are similar throughout the range of exercises. We will further expand on our reasoning for choosing this area in the task design section. Our contributions in this work are as follows:

(1) A modeling approach to systematically break down the knowledge conducive to the mastery of basic electrical circuitry using Q-matrix theory by aligning AR technology to learning outcomes.

(2) Defining and selecting the microskills required to perform a variety of electrical circuitry tasks.

(3) Design principles by microskill and findings of AR learning content implemented into an educational curriculum.

6.1 Related Work

In this section, we investigate a theoretical framing to build an AR-based curricula as part of our project Human Skilling.

6.1.1 Definitions for our educational context

Skill An ability which has been automated and operates largely subconsciously[285]. It may be broken down into smaller, more manageable components or microskills.

Microskill The specific ability, knowledge, aptitude or information required to perform a task. In cognitive assessment, the equivalent of a microskill is typically referred to as an "attribute" that a student may or may not have acquired [286].

Knowledge Space The set of microskills/attributes proven to be acquired by a student upon a successful completion of a task [287], [288].

Task The process or series of actions (steps) that are conducive to learning a skill, which can be decomposed into the interactions between users and equipment [289].

Item/Step The smallest segmentation of an action performed by a learner towards successful completion of a task [290].

Q-matrix An assessment matrix defined by step-microskill associations required to perform a task [291].

Ideally, an instructor as well as a learning sciences expert must be consulted to develop and elaborate a valuable matrix.

6.1.2 Cognitive assessment using Q-matrix theory

Cognitive assessment has surfaced as a new model of educational measurement that combines psychometric standards with the objectives of formative assessment [292]–[295]. The focus of cognitive assessment is on specific microskills, knowledge, and other characteristics that are necessary to perform tasks which are typically selected to assess a students' abilities. Cognitive assessment tests are customized to evaluate students' mastery of the learning content and provide immediate feedback on their strengths and weakness; thus, determining which microskills were learned or are in need of studying [287]. Each set of acquired microskills per student determines the proficiency class of the evaluated student.

The entire set of associations between items/steps and microskills is represented in the Q-matrix of a selected task [280]. The Q-matrix must be accurate and complete, which means it must provide all possible proficiency classes of the students [296]–[299]. The goal of this method is to obtain a linear system, which allows the application of standard linear boolean algebra techniques [300] and infer an unobservable knowledge space (what is going on in their minds) based on observable information in students' responses. Typically, the Q-matrix has been used to assess students' mastery based on multiple choice questions (e.g., mathematical, reading comprehension tests) [281], [301]–[304]. However, it has never been utilized in the context of AR, which brings an entirely new dimensionality to cognitive assessment (e.g., digital data vs. the real world). While multiple-choice tests require students to engage in cognitive tasks, an educational AR technology combines critical thinking and navigation within the virtual and physical world–hands-on and "minds-on" approach. In our case, students perform psychomotor tasks in an AR environment (e.g., select, manipulate, assemble, and interact with the environment), thus our landscape spans a brain-body-environment.

In this work, we carefully curated the decomposition of the knowledge necessary to perform a variety of electric circuitry by aligning the microskills to the AR technology. Further, we initiate key directions for how we can use the knowledge space generated to formulate a high-quality AR curricula.

6.2 Modeling

6.2.1 Preparing an Incidence Q-matrix

A Q-matrix maps the underlying processing skills necessary to complete a task, where the columns of the matrix represent the items or steps to complete a task and the rows represent the microskills required, or vice versa. The entries in each column are given a boolean value (true = 1 or false = 0) depending on whether that microskill is required for the solution of that step. Thus, as a boolean matrix, the Q-matrix is subject to the assumptions and theorem of boolean algebra onto which we will expand on as we develop our user studies. The user studies will aid us to exemplify the content and procedure of its formulation, and to dispel some doubts due to abstraction. In this section, we will present a simple example on a basic LED circuit (Fig. 6.2). This example will be represented by a 3 by 3 Q-matrix.

Microskill 1 (MS_1): Ability to understand current flow.

Microskill 2 (MS_2): Ability to understand polarity.

Microskill 3 (MS_3): Ability to understand circuit connections.

Step 1 (S_1): Connect two resistors in series.

Step 2 (S_2): Connect LED to resistors.

Step 3 (S_3): Connect LED(-) to battery(-) and resistors to battery(+).

The explanation of the microskills are the following [175], [305]:

MS_1: Current flow is a closed loop around a circuit with a power source (e.g., 9V battery) and a load (something to use up the energy, e.g., an LED). *MS_2:* Polarity is the correct direction in which connections between components are made (e.g., connect battery(-) to LED(-)) so that current can flow. *MS_3:* Connections are defined as the joining of electrical components to form a working circuit (e.g., a bulb, battery, and wires).

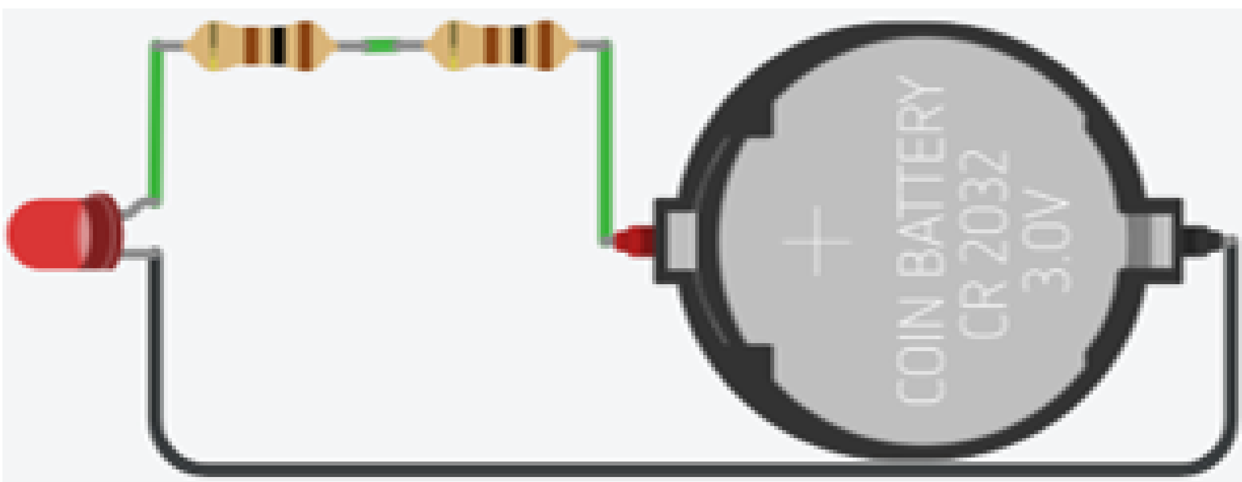


Figure 6.2. Basic LED circuit. Components: LED, 2 10Ohms resistor in series, and 3V batteries (Made with Fritzing).

$$Q = \begin{array}{c|ccc} & S_1 & S_2 & S_3 \\ MS_1 & 1 & 0 & 1 \\ MS_2 & 0 & 0 & 1 \\ MS_3 & 1 & 1 & 1 \end{array}$$

The Q-matrix showing the associations between the steps and microskills can be explained as follows going column by column: **Column 1.** Understanding of current flow (MS_1) (i.e., connecting one resistor after another so that the same current flows through each) and connections (MS_3) (i.e., understanding how to add the end of a resistor to another) are necessary to *connect two resistors in a series* (S_1), but knowledge of polarity (MS_2) is not necessary for this step because resistors are not polarized (i.e., orientation of the resistors is not relevant because current flows in both directions). Thus, the microskills required for S_1 are 1 and 3, which are translated to the column entries (i_{11},i_{21},i_{31}): 1, 0, 1. **Column 2.** Understanding of connections (i.e., understanding how to connect an end of the resistors to an end of the LED) is necessary to know how to *connect LED to resistors*, because a resistor is not polarized and the current flows in both directions from the ends of the resistors in series. Thus, the microskill required for S_2 is only 3, which determines the column entries (i_{12},i_{22},i_{32}) as: 0, 0, 1. **Column 3.** Understanding of current flow (i.e., closing effectively the current path of the circuit with the battery, resistors and LED), polarity (i.e., connecting LED(-) to battery(-) and available end of resistors(+) to battery (+)), connections (i.e., understanding how to connect an end of battery cap to the available end of the resistors and other end of battery cap to available leg of the LED) are necessary to know how to *connect LED(-) to battery(-) and resistor to battery(+).* Thus, for S_3 we need microskills 1, 2, and 3, which are represented by the column entries (i_{13},i_{23},i_{33}): 1, 1, 1.

6.2.2 Validating the Q-matrix

When we prepared our Q-matrix, we evaluated the microskill-step associations. However, by looking at the Q-matrix, we realize that some microskills have more value than others. For example, in our previous Q-matrix, MS_3 (*ability to understand circuit connections*) is necessary for all three steps, while MS_1 (*ability to understand current flow*) is needed for

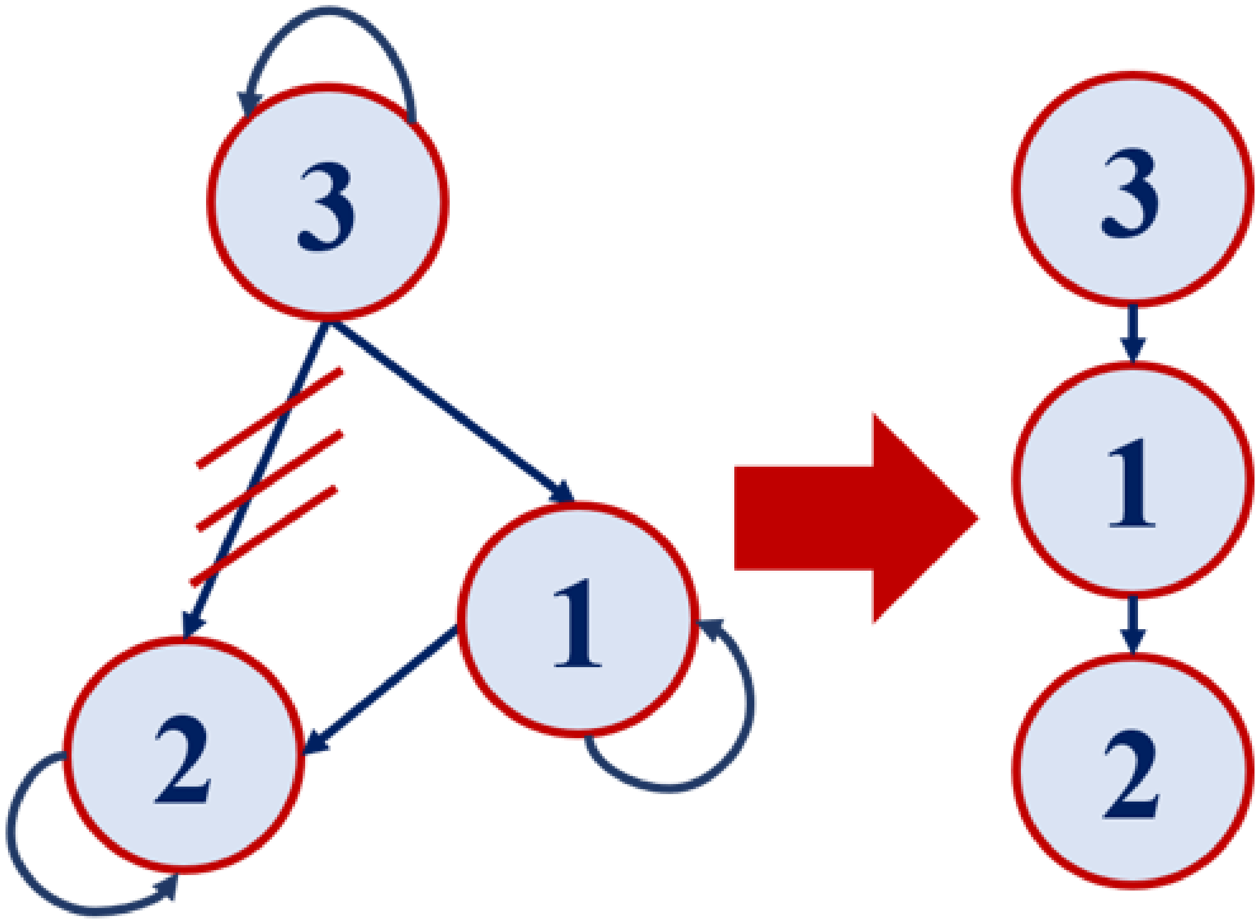


Figure 6.3. Left: Initial tree diagram of microskills. Right: Final tree diagram of skills.

two of the steps and MS_2 (*ability to understand polarity*) is needed for only one step. These microskills have a hierarchy among them. This hierarchy is easy to visualize because we have a small 3 x 3 matrix; however, a typical matrix will be much larger and have multiple associations. The reachability matrix (R-matrix) is a K x K matrix that represents the associations among microskills. Each row of the R-matrix represents an item that satisfies the specified hierarchical structure. We obtain the following R-matrix from our Q-matrix:

$$R = \begin{array}{c|ccc} & MS_1 & MS_2 & MS_3 \\ MS_1 & 1 & 1 & 0 \\ MS_2 & 0 & 1 & 0 \\ MS_3 & 1 & 1 & 1 \end{array}$$

We will elaborate on how to fill the entries of the first row of our R-matrix by using boolean algebra, which compares two distinct rows (microskills) of our Q-matrix. Entry i_{11}=1: Parent (higher hierarchy): (1,0,1) against child (lower hierarchy): (1,0,1), this is true because this row is compared against itself. i_{12}=1: Parent: (1,0,1) against child: (0,0,1), this is true because both rows do not contradict each other. i_{13}=0: Parent: (1,0,1) against child: (1,1,1), this is false because parent entry contains a 0, while the same child entry is a 1, and it does not make sense that a child would possess a microskill that the parent does not.

The R-matrix is the algebraic representation of the hierarchies between microskills, and it allows us to derive a tree diagram for a graphical representation of these hierarchies. If we observe Figure 6.3 (left), it is an exact representation of the R-matrix: MS_3 contains itself and also is the parent of MS_1 and MS_2. Similarly, MS_1 contains itself and is a parent of MS_2. Now, if we observe Figure 6.3 (right), we see the final hierarchy in order of MS_3, MS_1, and MS_2. We erase the self-containment symbols and also disregard the direct path from MS_3 to MS_2 because MS_2 is a child of MS_1. This final tree diagram is important to check if each microskill fits in the hierarchy of valuable concepts to teach the students. This **validation loop** (e.g., an instructor could start by the tree diagram, then the R-matrix, and finally produce the Q-matrix) of creating Q- and R- matrices and the tree diagram enables us to compare the original and the new Q-matrices, and make any modifications to the Q-matrices if necessary.

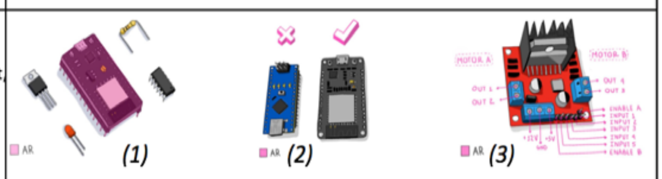
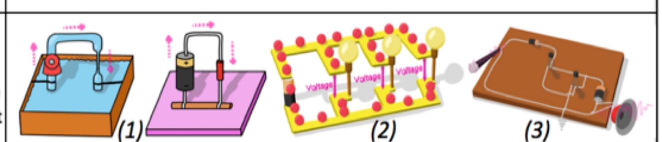
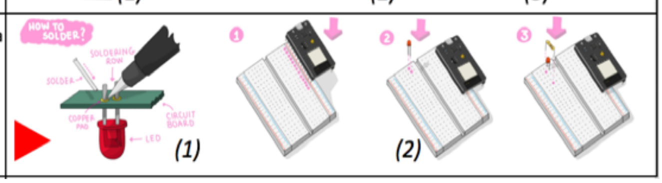
6.2.3 Students' knowledge space generated from the Q-matrix

After validating the Q-matrix, we need to collect the scores of an examination of the students' knowledge on the material. In our case, because we are dealing with novices, we must present them with the knowledge of all the microskills prior to the test. Once they familiarize themselves with the learning contents and complete the test, we can collect their answers. To exemplify how to calculate the knowledge space, suppose that *Student A* scores as follows: S_1=1 (correct), S_2=0 (incorrect), S_3=1 (correct). Since the student failed at S_2, this means that column 2 of the original Q-matrix has changed from: 0-0-1 to 0-0-0. We refer back to our Q-matrix to calculate the value of each microskill by summing every entry of 1 in each row (MS).

The mastery of each skill is the ratio of a MS value from the modified Q-matrix to a MS value from the original Q-matrix: MS_1=2/2=1, MS_2=1/1=1, MS_3=2/3=0.66. Then, it is up to educators to decide what the cutoff value is for expertise of the students. In our case, our suggested cutoff value is 70% (0.70) [280], which means that any calculated expertise that falls below this value, is a microskill that needs further studying. These results mean that the knowledge space of *Student A* is MS_1 and MS_2, which means that the student is lacking MS_3. We will provide the code we used to calculate the knowledge space of students. We have provided a general overview of Q-matrix theory; for more information refer to [280].

6.2.4 Design microskills in an AR environment

Table 6.1. Microskills aligned as AR content. AR content design principles based on the type of identified microskill.

Type	*Purpose*	*AR Content Design*	*AR Examples in Electronics*
Perceptual	-Bring users' attention to an object among objects cluster. -Get feedback on selection. -Provide parts, names, values, and functionality of objects.	-Change object color (e.g., use semi-transparent shader for ESP32)**(1)** -Match 3D model with physical object, give virtual feedback on top of object (e.g., ESP32 vs. Arduino Nano)**(2)** -Overlay information on physical model (e.g.,parts of L298N motor)**(3)**	
Cognitive	-Teach about long format concepts (e.g., principles, facts) -Explain abstract concepts. -Provide analogies to help users familiarize with concepts.	-AR animations (e.g., analogy to compare flow of water with current flow, to compare transistors with microphones and megaphones) **(1,3)** -AR effects (e.g., to represent current flow, voltage, etc.) **(2)**	
Motor	-Explain object manipulation and assembly. -Provide examples on how to perform an activity. -Demonstrate the steps to correctly finish a process.	-AR embedded video tutorials (e.g., a how-to solder video triggered when user selects the soldering iron) **(1)** -AR interactive examples (e.g., step-by-step procedural instructions that provide visual feedback to user) **(2)**	

As we explained in our related work section, there is little reference on how to design the AR content for an educational curriculum, as most classroom implementations were done using an empirical approach and typically focused on how to integrate AR into the classroom, rather than how to customize the AR content itself. Thus, we decided to approach the design with an *emergent coding* approach [306], in which we clustered the types of microskills we could recognize in AR: *perceptual* (i.e., time specific knowledge designed to attract the attention of the user and deliver visual information) [307]–[314]; *cognitive* (i.e., time specific knowledge to generate and collect information from the users' working memory) [17], [18], [315]–[319]; *motor* (i.e., time specific knowledge to properly perform an operation or process) [80], [84], [85], [320]–[323]. In Table 6.1, we go into further detail on the educational purposes for each type of microskill and guides on how to translate it into AR in terms of content design. We also provide some practical examples of AR in electronics in which the design techniques can be deployed. We anticipate that as learning content, any microskills must be accompanied by voice or text narration of the context.

Let us look at the microskills in our Q-matrix: *current flow*, which can be conveyed through the animation of invisible phenomena (e.g., long-format animation with electricity effects to show current): (cognitive); *polarity*, which requires both understanding the direction of current and recognizing the shape of an object to indicate positive and negative terminals (e.g., an AR animation to demonstrate current flowing through + and - terminals and overlaid information in the form of plus and minus signs to each terminal of the LED): (perceptual-cognitive); *circuit connections*, which requires manipulating components based on circuitry logic (e.g., AR interactive example): (motor).

After following the design principles for what the microskills will look like, we have to determine how these will be presented to the users. In scaffolding methodology for multimedia, the technology fades away as the student completes the tasks and slowly becomes more independent. This process is a key aspect in aiding learning success [324]–[327]. If we select several tasks that are conducive to learning the skill (i.e., electrical circuitry), it follows that after each task, based on the student's performance–whether each step was completed correctly or not–we can re-calculate the student's knowledge space. This knowledge space determines which microskill the student is lacking, for example, MS_3 (*circuit connections*). Thus, we will test two AR conditions: (1) **PartialAR**, which only presents the student with MS_3, emphasizing on this knowledge gap; (2) **Full-AR**, which presents all microskills MS_1, MS_2, MS_3, to let the student explore which AR content they want to review. Based on the design principles, we will prepare the microskills for several tasks, and based on our two AR conditions, we will evaluate our user studies.

6.3 The Tasks

6.3.1 Electrical circuitry

Electrical circuitry was placed in an area of broader investigation as a part of the surge of interest in acquiring knowledge through a hands-on, minds-on approach (National Research Council 2012) [5]. Thus, we will use AR to encourage students to grasp the concepts "at hand" and visualize "hidden factors" (e.g., current, polarity, etc.) while making an operating circuit, and go beyond following a series of steps to build a working circuit.

This is particularly prescient because misconceptions of how circuits work have been found even in undergraduates from physics and engineering courses [328]. Two of the researchers have had previous experience shadowing an IoT development course for undergraduates without previous background on electronics.

While some of the microskills were extracted from existing literature on elementary knowledge on electric circuits (e.g., current flow, polarity, connections, series, parallel) [175], [305], [329]–[331], the remaining microskills were derived from class observation and scrapbooking (note-taking and pictures), mainly during the first five weeks of classes (3 hours weekly). The two researchers, along with a learning sciences expert outlined the learning outcomes for each one of the microskills.

In Table 6.2, we give an in-depth explanation of the learning outcomes that we set as goals for each microskill. These microskills were selected from existing literature on basic concepts of electrical circuitry that are pervasively misunderstood [174], [175], [305], [329]–[333]. The following meta-steps were not explicitly given to students, but these were meant for the researchers to prepare the general Q-matrix 6.3 and to keep *score* of correct and incorrect steps by students. In such a way, after every task, we can re-calculate the knowledge space for each student.

Table 6.2. Microskills and learning outcomes.

Microskill	Learning outcomes
Ability to understand current flow	■ Understand the circular path of electrons around a circuit. ■ Understand the difference between an open circuit and a closed circuit.
Ability to understand polarity	■ Learn to connect components in which current flows in one direction. ■ Learn to read polarized components, e.g., the positive (longer) leg of an LED needs to be connected to the positive terminal of the battery. Other components with polarity: capacitors, batteries, power supplies, transistors, voltage regulators.
Ability to understand resistance	■ Understand the opposition of a component to the flow of electric current. ■ Learn that electricity always follows the path of least resistance to ground (beware of short circuit).
Ability to understand connections	■ Understand the connections between one component and another, with emphasis on the terminal ends of conductivity. ■ Learn that every component must be well connected to power the circuit (e.g., battery, bulb, and wires).
Ability to recognize components	■ Learn to recognize 3-5 components and their functionality from memory. ■ Learn to read the shape and terminals of each component.
Ability to understand breadboard logic	■ Learn to understand the governing principles of breadboard connections and parts of the breadboard. ■ Understand how components may be inserted into the breadboard and how to connect them to each other.
Ability to understand series circuits	■ Learn to connect components in series, in which the current only follows one path. ■ Understand that series components are connected to follow a single path, without being separated by any branches (e.g., a string of LEDs).
Ability to understand parallel circuits	■ Learn to connect components in parallel, in which the current is divided into two or more paths before recombining to close the circuit loop. The voltage across every component in the circuit is similar. ■ Understand that for two components to be connected in parallel, both ends of each component (e.g., LEDs) must be connected together.
Ability to read specs sheet	■ Learn to read the tables or descriptions that explain the terminals and connections of each component. ■ Understand the diagrams which will be overlayed on the component (e.g. do not use an input only terminal from a component if you require an output).
Ability to read resistor color code	■ Learn to read resistor values from left to right towards the golden band. ■ Consult the color value chart to learn the resistor values from the first two colors, the multiplier from the third, and the tolerance from the fourth (golden).

6.3.2 Meta-Steps

A. Locate <insert list of components> for circuit assembly.

B. Place and fit <insert microcontroller type and miscellaneous component(s)> into the breadboard.

C. Find and interpret specs sheet of <insert microcontroller type and miscellaneous component(s)> to identify the digital and analog connectivity pins.

D. Connect <LED cathode> to ground <rail of breadboard or pin of microcontroller>.

E. Connect <LED anode> to <resistor>.

F. Connect <resistor> to <digital pin of microcontroller>.

G. Connect <digital pin(s) or analog pin(s) or power pin or ground pin of miscellaneous component> to <digital pin(s) or analog pin(s) or power pin or ground pin of microcontroller>.

Note: The complexity of this step depends on the amount of required connections between the microcontroller and the miscellaneous components.

H. Connect <power, ground of miscellaneous components> to <power, ground of microcontroller>.

I. Connect ground and power <pin(s) of microcontroller> to ground and power <rails of breadboard>.

J. Connect ground and power <battery terminals> to ground and power <rails of breadboard>.

The information inside <> can be modified depending on the task at hand; however, the general structure of the steps is similar across tasks.

6.3.3 Study

We recruited 20 undergraduates (55% male, 45% female), ages ranging from 18 to 34 *(Mean=23.1, SD=2.69)* to participate in our studies. All participants reported no significant background in electrical circuitry or physics *(Mean=1.25, SD=0.43)* from a 1 (novice) to 5 (expert). Participants were split into two conditions (FullAR vs. PartialAR) and each student participated in an individual session 1 (*2 hours*) and session 2 (*2 hours*) of the user study. We scheduled each student for session 1 and 2 exactly one week apart from each other.

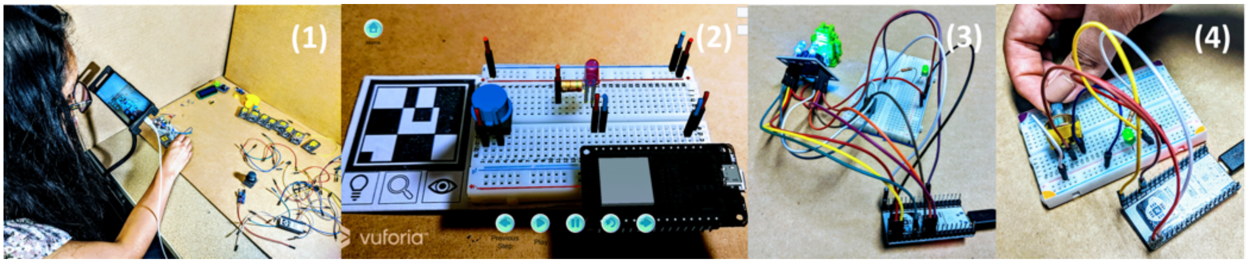


Figure 6.4. (1) Phone-AR setup, (2) procedural AR (example), (3) task 2: color sensor (green) turns on LED, (4) task 4: potentiometer controls LED.

The microskills were delivered using AR technology as the fundamental knowledge that were required to complete the tasks, and which could be accessed at any time by the participants during the sessions. Apart from the two interactive examples (AR tutorials), which provided a series of procedural AR animations on how to assemble a working circuit, there were no additional instructions provided to students. Prior to each task, the researcher provided the students with a description of the outcome for each task (Fig. 6.4). For example: *"You need to set up a circuit in which you use your ESP32 (microcontroller) so that every time you press down on your pushbutton, you turn on the LED"*. Every microcontroller had the uploaded code for the task and the specs sheet provided for each component contained the pin numbers from the microcontroller that had to be used.

First session for PartialAR condition was as follows: Students started by exploring all 10 microskills + interactive example 1, followed by a test (Task 0), then once each student's knowledge space was calculated, we exposed the participants to the microskills found lacking as they performed Task 1. For the FullAR group, similarly, participants started by exploring all 10 microskills + interactive example 1, followed by Task 0, then we again gave them access to all the microskills as they performed Task 1.

Second session session for PartialAR condition was as follows: Prior to every task we re-calculated the new knowledge space of each participant and provided participants with the customized AR based on the microskills that were found to be lacking. For the FullAR group, participants performed Tasks 2-8 with all 10 microskills made available at each task.

Table 6.3. Prepared Q-matrix for all selected tasks.

Microskills \ Steps	A	B	C	D	E	F	G	H	I	J
MS_1: Ability to understand current flow	0	0	0	1	1	1	1	1	1	1
MS_2: Ability to understand polarity	0	0	1	1	1	1	1	1	1	1
MS_3: Ability to understand resistance	0	0	0	0	1	1	0	0	0	0
MS_4: Ability to understand connections	0	0	1	1	1	1	1	1	1	1
MS_5: Ability to recognize components	1	1	1	1	1	0	0	0	0	0
MS_6: Ability to understand breadboard logic	0	1	0	1	0	0	0	0	1	1
MS_7: Ability to understand series circuit	0	0	0	1	1	0	0	1	1	0
MS_8: Ability to understand parallel circuit	0	0	0	1	1	0	0	0	0	0
MS_9: Ability to read specs sheet	0	0	1	0	0	0	1	1	1	0
MS_{10}: Ability to read resistor color code	0	0	0	0	1	1	0	0	0	0

The tasks and interactive examples presented to students were in the following order: **Session 1: Interactive example 1**: Turn on LED when *pushbutton* is pressed down. **Task 0**: Turn on LED when ultrasonic distance sensor detects an obstacle (e.g., a hand) at a certain proximity. **Task 1**: Turn on LED when distance calculated by *obstacle detector* sensor and an obstacle (e.g., a hand) falls below a threshold. **Session 2: Interactive**

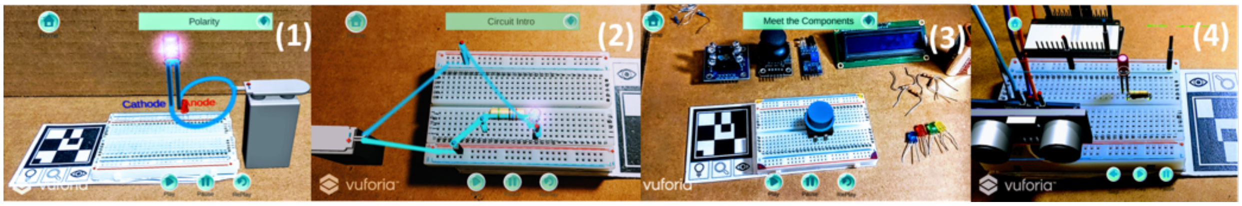


Figure 6.5. Overview of microskills: (1) polarity, (2) current flow, (3) components. (4) Interactive example: procedural instructions of ultrasonic sensor control of LED.

example 2: procedural instructions for Task 0. **Task 2**: Turn on LED when *color detector* sensor detects a green object in its path. **Task 3**: Turn on LED when the temperature detected by the *humidity and temperature sensor* reaches a threshold. **Task 4**: Control the intensity of the LED using the *potentiometer*. **Task 5**: Turn on LED and display a message on the *LCD screen* (e.g.,"Hello World"). **Task 6**: Turn on LED when *joystick* is pressed down. **Task 7**: Connect three 100Ohms resistors in series to sum up to a resistance of 300Ohms, then use the *pushbutton* to turn on LED when pressed. **Task 8**: Connect four 1kOhms resistors in parallel to lower the resistance to 250Ohms, then use the *pushbutton* to turn on LED when pressed. Note that the microskills available for studying were available throughout the tasks depending on the AR condition (Fig. 6.5).

6.4 Results

6.4.1 Keeping score during the tasks

In order to re-calculate the knowledge space, the researchers took note of whether each student had completed each step correctly or not. **Each step performed correctly adds a 1-point score to a participant's total.** We performed a one-way ANOVA test to compare the means between the two conditions (Full AR vs. Partial AR) on two sessions (1st session vs. 2nd session). There was a statistically significant difference between the two conditions as determined by one-way ANOVA ($F(3, 36) = 49.61$, $p = 0.00$). A Tukey post hoc test revealed that the average score–*out of 10 points, which represents 10 microskills*–for the PartialAR was statistically higher for the second session. There was a statistically significant difference between FullAR-1st session (3.7±1.55) and PartialAR-1st session (5.7±1.27) groups (p = 0.002), with the PartialAR condition enabling students to outperform the FullAR condition. We also determined a statistically significance between FullAR-2nd session (7.98±0.51) and PartialAR-2nd session (9.34±0.47) groups (p = 0.04). **We found the PartialAR condition presented to students in the form of their re-calculated *knowledge space* enabled statistically significantly overall higher performance than FullAR in both the first and second sessions.**

6.4.2 Assessment by microskill

We wanted a breakdown assessment of the participants' performance for each microskill, to determine which microskills they found the most difficult, and whether these matched our observations. Our overall breakdown of their average score per microskill (MS) is as follows: MS_1 = 9.94 ± 0.17, MS_2 = 9.44 ± 1.16, MS_3 = 9.89 ± 0.33, MS_4 = 7.63 ± 2.16, MS_5 = 8.44 ± 1.70, MS_6 = 6.75 ± 2.96, MS_7 = 8.06 ± 2.03, MS_8 = 8.31 ± 1.83, MS_9 = 8 ± 2.49, MS_{10} = 9.25 ± 1.26. We compared the lowest score of the two skills by performing a paired t-test between MS_4 and MS_6. MS_6 **was statistically significantly more difficult than the population normal performance score for all tasks, t(15)=2.21, p=0.02**. We found no statistically significant difference between the following bottom two: MS_6 and MS_7 (p=0.22). This is consistent with our observations that *breadboard logic* was the most difficult microskill, as the most common mistake took place when students would hesitate or get confused on how to 'close' the power and ground of the circuit in the power rails.

6.4.3 Think-aloud understanding of circuitry

Following the skilling part of our first sessions in which we presented the students with all relevant information, we deployed the think-aloud method [334] to evaluate the thought process and logic used to complete different circuit tasks. We repeated similar questions at the end of the first session and at the end of the second session. One of the researchers conducted the majority of the transcription, while another researcher coded 40% to achieve interreliability. There was moderately strong agreement between both of the researchers' judgements, $\kappa = .773$ (95% CI), $p < .0005$.

The following are snippets of a conversation carried out between Researcher 1 (R1) and Participant 9 (P9) during the assessment part (task 2) of session 1:

R1: Do you have a sense of what your closed circuit will look like? What will happen?

P9: At the end of the circuit? I'm going to connect it to the [ultrasonic distance] sensor, and if all is well then the light is going to turn on (*inserts resistor into the breadboard*) R1: Yes, that's the idea. Do you have a sense of why you are using a resistor in your circuit?

P9: To try to lessen the electricity that goes to the light, to avoid breaking the light (*points to LED in breadboard*).

R1: Do you have a sense of what the ends of the LED are telling you?

P9: Smaller part is the cathode and the longer part is the positive part. R1: Do you have an idea of how to connect your sensor to the board?

P9: Not too much, but I have to try to have the electricity go through all the board. I'm just not sure how to connect it, I guess (*participant proceeds to multiple trials to connect the circuit*)

R1: Is your circuit closed? Why?

P9: I don't know...This is it? (*participant hands it over to researcher*).

Most participants still had many questions about the content after the first session, but the second session concluded with participants being capable of providing proper, coherent responses about their circuits. We will expand on these observations in the *Findings* section. For example, the following are snippets of a conversation carried out between Researcher 1 (R1) and Participant 15 (P15) towards the end of session 2 (task 8):

R1: So do you have a sense of how a closed circuit looks like?

P15: I have to go from positive charge to a negative charge. So I always know that I have to go from the power to the ground and everything has to be connected so that it will light up the LED...(*explains her circuit in much greater detail*).

R1: Do you know why we were using the resistor in the circuits? (*points to the resistor in the board*)

P15: So I know that [the resistor] controls the current, so, like, it would make sense to regulate how much current gets through and not break the LED. (*points to the current going from ESP32 to resistor to LED*)

R1: Do you know what the LED having a long side and a short side mean?

P15: Yeah, this shows the polarized sides, so that the long side shows the positive side and the negative side goes to ground–negative side goes to ground, positive side goes to power or load (*holds ends of the LED and spreads them with hand*).

R1: How do you check that your circuit is done? (*no load is applied yet*)

P15: I would make sure that if I have a sensor–like the color [sensor]–, have to make sure it goes to the pins, and so like, these pins [from sensor] go to these pins of the ESP32, then the ground or the power from that sensor is on the board for the positive and negative charge, and then I make sure that the LED starts from the resistor. So I make sure that everything has current. I think of it as a circle that I need to close. (*points to all components in breadboard one by one*).

6.4.4 Post-tasks multiple-choice examination

At the end the second session, we decided to test the students with a multiple-choice questionnaire, in order to evaluate their understanding of each microskill. The test included 10 questions, in which each question was meant to target one or more microskills. We compared the average score between the two conditions by performing a two-sample t-test assuming unequal variances and we found that there was no statistically significant difference between both groups, $t(13)=-0.412$, $p=0.34$. For example, some of the questions included: *choose the schematic of a working circuit*, *choose the functionality of a resistor*, *read the value of the following resistor*, *which of the following is true about this series circuit?*. We found that participants score for both conditions was higher than expected (70% cutoff), **scoring an average of 8.8 $\pm$ 1.49 for the FullAR condition and 9.03 $\pm$ 0.69 for the PartialAR condition out of the 10 points for the questionnaire.** This means that as students got more access to AR, the difference between conditions disappears.

6.5 Qualitative and Quantitative Findings

6.5.1 Adoption of a new vocabulary as evidence of learning

Building a circuit does not necessarily translate to understanding concepts, which is why we used the **think-aloud** method to follow and gain insights into students' learning process. Researchers noticed that as students became more exposed to the concepts of electrical circuitry, they became more articulate and began adopting words they had no familiarity or use for, previously. After the first session, students had somewhat vague ideas about the concepts recently introduced and that was also reflected on how they answered the questions. Participants used vague words such as 'thing', 'energy', 'light' or pointed to objects to talk about the components, concepts they wanted to explain or often said that they were unsure of what was going on. For example, they phrased their statements as *'I think that the resistor is used for...'* (P3) or responded a question with another question, such as *'Yes, I kind of remember...what is the name of this?'* (P16, referring to the ESP32). Since this was an assessment session, we were not expecting them to fully understand or internalize the microskills, but it was useful to compare their answers to the knowledge space we calculated for each student. Students were found to be lacking several microskills (especially cognitive), which meant they needed studying more of the AR content.

Then towards the end of the second session, once participants had a chance to become familiar with their circuits and AR environment, we asked questions and told participants to walk us through their logic. The researchers observed that as participants successfully completed all the tasks, they also gained fluency on the concepts and the objects they were manipulating. For example, they adopted words like 'voltage','closed loop', 'charge', 'current', 'anode', 'cathode'. Another important development was that **as the participants became fluent with the new vocabulary and concepts, they were capable of faster troubleshooting of their circuits**. For example, the most common mistakes throughout the tasks were related to breadboard logic (MS_6), as participants would often forget to close the loop by connecting power or ground terminals to obtain their working circuits. Upon trying and failing to power their circuits, most participants first instinct was to check these types of connections.

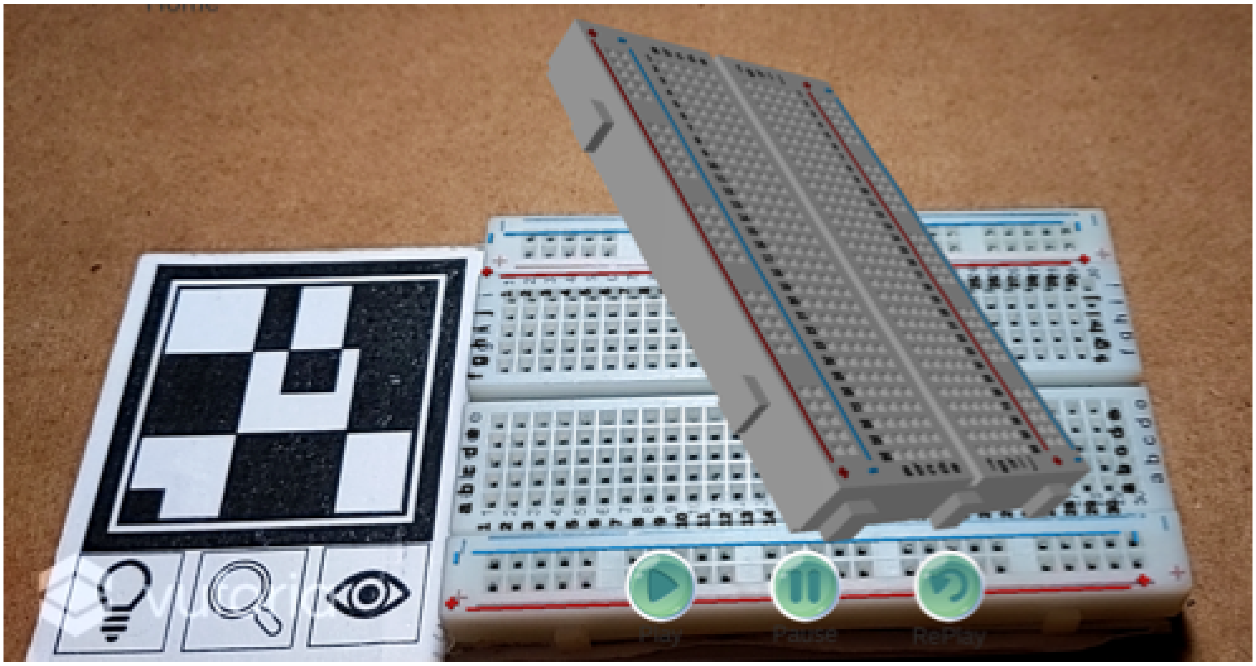


Figure 6.6. (Bottom) New transparent shader (virtual) overlayed on physical breadboard, power and ground rails, numbering and letters of breadboard are the non-transparent features. (Top) Previous solid shader, which had to be discarded due to occlusion issues.

6.5.2 Improvement of the AR content

Following the first assessment session, we were able to pick up on participants' first impressions on the AR technology. Participants found AR to be useful and wanted to explore it to further understand electrical circuitry. We questioned them on what they liked and did not like from the AR content:

Occlusion and misalignment control.

Some participants raised concerns about the breadboard shader (i.e., the virtual breadboard superimposed on the physical breadboard), because it occluded the physical breadboard and their hands, which made confusing to follow along the interactive examples (*connections*). Also, electrical components are quite small, which means that the object tracking in AR is not as accurate as it would be with larger objects. While the tracking accuracy using QR codes only presented minor misalignments, when combined with the shader occlusion, it enabled more mistakes during the examples because participants could not follow and match the pins. Thus, prior to the second session, we used some techniques to bypass these issues. For example, we created an invisible shader to keep a virtual model in which the components would fit–but would not occlude the hands–and we also added the symbology of the power rails and the numbers and letters typical to a breadboard (Fig. 6.6). Then, we used AR to project the pin numbers of a component (e.g., resistor to pin *D23* of ESP32) in large letters. Another way to go around any confusion, was to encourage users to explore the zoom functionality of the AR technology in which they could simply read the letters and pins from components and match them during assembly, however the importance of matching specific pins between components was not obvious until we emphasized the name or number of each pin. These new design schemes were helpful to participants during session 2 and eliminated errors during the interactive examples, which were important to understand *breadboard logic* and *connections*.

Interactive AR is better than embedded video.

We had decided to provide one interactive example per session to enable participants to explore connections between components and how to manipulate them. These examples were considered complementary to further internalize the *ability to understand connections*, which was already explained in an embedded AR video. However, based on participants' responses, we learned that these examples were essential rather than complementary, because participants understood *connections* only after following along and building a working circuit and manipulating components with their own hands. Thus, we needed to make sure that the interactive examples were easy-to-follow and that participants could explore electrical phenomena and the components. For example, we had to play with the transparency of the components, so that too many wires would not occlude each other and we only kept the terminal ends of the wires to not confuse the participants. This type of 3D object exploration is particular to AR technology and participants preferred being able to explore the components in this way.

Voice narration was key and analogies worked best for complicated concepts.

According to participants' responses, voice narration–which accompanied every microskill–was useful to provide long format context and explanation of the different concepts, and requested it to be included in the interactive examples for the second session. Also, analogies were described as extremely useful to understand new concepts. For example, several participants brought up how helpful it was using a water flow analogy to relate it to current flow (see Table 1), and how analogies helped them think of electrical circuitry in their own terms (e.g., a circuit as a circle).

6.5.3 Full AR vs. Partial AR

As observed in the results section, partial AR enabled participants to have a superior performance in their overall score. Participants with full AR had access to all the microskills–even the ones they had already mastered–which typically meant that although participants could freely explore all the microskills, they were lost as to what specific knowledge they were missing since it was not emphasized among all the information. The group with PartialAR showed overall superior performance through their access to targeted microskills, which meant that after every task, they were directed to exactly the knowledge they had missed. However, as both groups continue exploring the learning content and completing more tasks, the difference between their scores (i.e., the gaps in their knowledge spaces) becomes insignificant as most students successfully finished the last task with almost no errors, and this is also observed in their written examinations (post-tasks). Thus, we can determine that **PartialAR–scaffolded AR based on the missing gaps of participants' knowledge spaces–can be particularly beneficial at the beginning of the learning process, as participants struggle to acquire new knowledge.**

6.5.4 Aligning the microskills to AR design principles

We leveraged the expertise of the researchers–who were previously involved in electrical circuitry classes and workshops–to carefully select the microskills necessary to fulfill the variety of circuitry tasks. This part of the process is fundamental to create a Q-matrix, map the associations among the microskills and steps, and to validate the hierarchies among the microskills. The results showed that the microskills were accurate and sufficient by obtaining a high average score *M=8.96* for all participants. In order to decide how to best represent the microskills in AR, we referred to Table 1 to select whether the microskills were perceptual, cognitive, motor, or often a combination of these. For example, *recognize components* was best exemplified by highlighting each component on the breadboard (*perceptual*); *current flow*–which can be considered an invisible electrical phenomena–was best represent in long format by an animation with electrical effects (*cognitive*); *connections* required manipulating components based on circuitry logic *motor*, and we concluded that an AR embedded video followed by an interaction example worked best to educate the students. **Our listed AR content design principles from Table 1 are not meant to be binding, but meant to be used as a guide to deliver learning content to the students**. We suggest considering those techniques which are coded specifically to deliver small segments of information–microskills–to the students.

6.5.5 Achieving learning outcomes in AR

Each microskill we selected was accompanied by at least two learning outcomes. Selecting learning outcomes for each microskill is not part of Q-matrix theory which generally determines the students' knowledge space based on performing correctly each step of the task. However, setting achievable goals for each microskill allows us a concrete metric to test the knowledge of each student. In the case of the multiple-choice examination, we designed each question to address the learning outcomes of acquired knowledge we expected them to have. For example, one of the questions asked the students about the names in a list of 6 *components*. Every participant answered the question correctly and the overall average score for all participants was quite high.

6.5.6 Limitations in our experiments

Our experiments handled a relatively small sample size from an undergraduate population at a US university. We would need a much larger and diverse population to obtain a conclusive list of microskills that would be sufficient to enable novices to obtain the basic skill of electrical circuitry. However, the results were quite promising across tasks and examinations, and the authors would like to encourage similar experiments to be conducted in order to use our list as part of an electrical circuitry curriculum. Also, our model could potentially be applied to other multimedia successfully (e.g., video tutorials, 2D animations), which do not necessarily need to be embedded into an AR environment. However AR is a particularly useful tool capable of improving performance and spatial skills for highly spatial tasks (e.g., assemblies, connections, repairs), and we also observed from our own experiments that embedded video was not as effective as AR in order to explain some concepts, and that participants only learned them by making their circuits. When deciding whether AR is the right useful tool for a classroom, it is important to carefully analyze if the selected educational tasks would benefit from the use of AR.

6.5.7 Future work and potential of AR technology

We want to implement an AR-based curriculum for the next iteration of the electric circuits and IoT development course for undergraduates, in which two of the researchers will be instructing. Our workflow will be used to bring the novices to an elementary knowledge of electrical circuitry. This was one of the reasons we chose to use phone-based AR, so that we can make the learning material scalable and accessible to the students even prior to class or to long distance students. The first few iterations of this curriculum will be considered experimental, but it will help us continually refine the curriculum and the tools we will be using to teach the novices. Similarly, it would be interesting to see our workflow implemented in other subject areas (e.g., physics, chemistry, biology, etc.).

6.6 Conclusion

In this paper, we presented the use of Q-matrix theory as a design framework to develop an AR-based curriculum. This workflow systematically implements AR learning content using cognitive assessment into an education curriculum, in our case for mastery of basic electrical circuitry. Thus, we provided a list of suggested design principles to be used as a guide to deliver AR educational content. We evaluated the association between microskills–the smallest segment of knowledge–and steps, to complete diverse and complex tasks. In our evaluation, we demonstrated that scaffolded AR worked better when students were recently introduced to the novel concepts. In order to prove the learning of electrical circuitry in our participants, we used three types of evaluations: quantitative scores taken from each completed task, think-aloud method to follow their acquisition of new vocabulary and learning process, and a written examination (after second session) to verify their understanding of circuitry concepts. Thus, we proved that our workflow effectively leads to novices acquiring basic knowledge of electrical circuitry. Finally, we demonstrated that aligning the AR technology to specific learning objectives paves the way for high quality assessment, teaching, and learning.

6.7 Funding

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6.8 Authors' contributions

AV conceptualized and designed the work; participated in acquisition, analysis, and interpretation of data. ZL worked on content design and conceptualization. YK worked on acquisition, analysis, and interpretation of data. ZZ also worked on acquisition, analysis, and interpretation of data. KP has drafted the work, conceptualized it and substantively revised it. TR has drafted the work and substantively revised it. KR has drafted the work and substantively revised it. All authors read and approved the final manuscript.

6.9 Acknowledgements

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7. SUMMARY AND FINDINGS

My contributions to this thesis are the following series of solutions that enable instructors and designers to create AR experiences in collaborative and distant classrooms: MetaAR, an AR-based platform that enables collaborative authoring; RobotAR, a robotics toolkit which enables teleconsulting and creating AR-based makerspaces; ColabAR, a toolkit for quick-prototyping of collaborative AR-based laboratories; and a modeling approach to systematically break down the knowledge conducive to the mastery of basic electrical circuitry by aligning AR content to learning outcomes.

RQ1: To what extent do AR technologies lead to an improvement in students' learning?

In Chapter 2 (MetaAR), we propose that a STEM classroom which includes an AR technology platform can be divided in the following categories to promote learning: **work, design, collaboration,** and **technology**. **Work,** refers to the manipulation of tangibles with superimposed AR, which translates to facilitating the discovery of underlying phenomena and STEM concepts (e.g., an error in the connections, that keeps current from flowing across the conductive ink pathway). **Design,** refers to instructors or students creating AR content (e.g., annotations, arrows, navigational cues, hints) inside an original AR environment, that can then be shared with the entire class or with a student. **Collaboration,** refers to the interactions that are supported by the architectures of the AR systems, in particular to improve the quality of the learning content (e.g., steps or animations to complete an AR-based project). **Technology,** refers to the AR system enabling new—contributed to—versions of the AR project to be made available to the class. These categories which were identified in MetaAR point to the classroom being transformed by the advent of AR technologies and also to an improvement in the learning experience by students being able to complete complex STEM (e.g., electrical circuitry in a "smart city") projects.

MetaAR focused on a co-located learning experience to create, modify, and share AR projects supported by a collaborative architecture. MetaAR supports our initial hypothesis that problem-solving works better as a collective experience. Inasmuch as problem-solving, a decrease in overall time to complete the project (of about 25%), and a decrease in overall error rate (of about 40%) by the class–while solving a difficult project–can be associated with a positive learning experience, MetaAR showed that the AR system improves the learning experience as compared to a traditional classroom without AR. When students worked on solving the original AR project, we observed that scaffolded AR instructions were conducive to independent inquiry and that students wanted to explore or discuss questions with each other. In our case, the distribution and accessibility to the AR educational contents was managed as a Q&A forum. For an analogy, we can refer to Stack Overflow, except that instead of doubts or questions from the students being answered with code, they were responded by other students adding AR content to the original project.

RobotAR focused on teleconsulting to provide teachers with a 3D perspective of their students' workspaces to support distance makerspaces and project-based classrooms. In RobotAR, we compared the use of our teleconsulting robotic toolkit and compared it to Zoom, which has been typically used in distance learning, especially during the pandemic. In this work, we also wanted to investigate whether perspective and repetition were important for hands-on learning of a subjects that requires performing spatial tasks. RobotAR enabled students to repeat AR-based instructions be played (and re-played) in-situ. For instance, students were able to watch instructions on a common circuit (e.g., the current mirror) being played directly on their breadboard. The use of RobotAR demonstrated an increase of 23 % in learning gains with respect to relevant electrical circuitry concepts and their relationship to spatial tasks, and a two-time increase in the completion rate of all tasks selected for the workshops, as compared to the Zoom workshops.

ColabAR, which continues with our efforts towards improving distance learning, was our attempt to satisfy the unique necessities of the laboratory classroom. While most of this work focused on the collaborative experience, we also learned that a realistic physical feedback (e.g., vibration to simulate pouring a chemical substance into a beaker) is an important feature that enables following through a laboratory similarly to a traditional laboratory setting. ColabAR showed that an AR-based laboratory enables students' performance (i.e., lab completion rate, lab scores) to be similar to their performance in an in-person laboratory.

The educational contents for AR can be scattered and confusing, and these new types of technologies require new ways to structure content. Thus, in Chapter 6, we focus on AR content design to systematically structure content and visualization of AR. This work reinforced our previous findings (Chapter 2) that scaffolded instructions lead to higher learning gains. Chapter 6 shows that structuring learning content into microskills, accompanied by learning outcomes, and then aligning them to AR content leads to an increase of about 90 % learning gains in students.

RQ2: To what extent do AR technologies enable the instructor to offer timely and on-point instruction during problem-solving?

In Chapter 1, we mentioned that the unique nature of AR technologies allows for selecting and manipulating of 3D objects [8]. AR objects being superimposed in the physical world provides multiple perspectives to spatial educational contents. Thus, it makes sense that when instructors need to deliver AR content, they also need spatial perspective and accessibility to the students' environment (i.e., workspace) to understand the problem and correctly position the educational content. Chapter 3 and 6 were deployed in the context of achieving electrical circuitry lessons, which require hands-on tasks and thus, make the perfect use cases to implement AR technologies.

The mobility and accessibility enabled by RobotAR, provided instructors with a 360-degree perspective of students' workspaces. During teleconsulting, instructors used the ability to zoom-in, tilt, and rotate the robot's camera to find out what the problem was, where to overlay the instructions, and how to engage the students. The results show that instructors and students are given a more productive teleconsulting experience with a decrease of about 30% in average teleconsulting time than by using Zoom videoconferencing.

In Chapter 6, our model divides a knowledge space (i.e., electrical circuitry) into microskills that are classified as: perceptual, cognitive, and motor. Table 6.1 provides suggestions to the alignment of microskills to AR content but the chapter also explains that different steps in a task may include more than one microskill at a time and thus, it may be necessary to use a combination of the visualization schemes we suggested. The learning gains shown in this chapter, suggest that carefully curating education contents and then aligning them to AR is a step in the right direction for instructors towards systematically designing and delivering AR.

RQ3: To what extent do collaborative AR technologies influence students' engagement and interest?

In Chapter 1, we discussed how AR contents were often coupled with multimodal technologies (e.g., visual cues, haptics, robotics, 360-degree scene reconstruction) to deliver educational contents. AR technologies already provide new interaction modalities that are introduced into the classroom. Thus, when comparing collaboration architectures and systems, we evaluated whether the improvements in students' engagement ad interest was due to the novelty of AR or AR combined with these multimodal technologies. In Chapter 2 and Chapter 4, we make sure to include at least one user study to evaluate AR vs. AR + collaborative architecture (e.g., pull-based model, haptics). In MetaAR, we compare AR vs. AR with implementation of the pull-based model. Our AR system that implemented the pull-based model kept track of specific to measure students' engagement and interest in the educational content. We found that when we presented students with the option to volunteer AR learning content to help classmates or ask for help themselves, students volunteered contributions to the original AR project at twice the rate they asked for help. In ColabAR, the AR content was the basis for students' laboratory partnership, while the haptics was the basis for the communication between the partners. When comparing AR vs. AR with haptics, students reported that the haptics in particular, enabled them to transmit information, intention, and successfully communicate with a partner about 75% of the time.

Our hope is that this thesis provides a pathway towards more natural interactions and advances in our understanding of the use of AR technologies for co-located and distance learning, which are becoming increasingly important in today's classrooms.

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