ShARed IoT: Designing Shared Experiences in Co-Located Spaces with Augmented Reality and Internet of Things Devices

ANONYMOUS AUTHOR, Institution
ANONYMOUS AUTHOR, Institution
ANONYMOUS AUTHOR, Institution

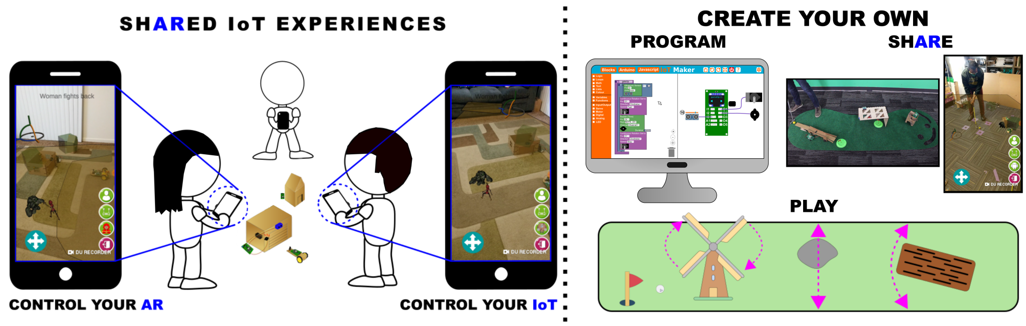

Figure 1: *ShARed IoT is a mobile augmented reality system that can wirelessly communicate with custom built electro-mechanical IoT devices. Cloud Anchors enable the sharing and control of all AR content across multiple smartphones, and our wireless communication protocol enables control of IoTs across those smartphones. Using ShARed IoT, we study how users can use the system to create unique AR-IoT interactions and some classroom applications.*

Incorporating physical and computing devices alongside AR presents opportunities for shared experiences between users, leading to more engagement. Such shared experiences create opportunities for social interaction, ideation and creativity. In pursuit of a future where novice makers can create unique experiences, and subject matter experts can create dynamic, interactive, and engaging AR content, we present our solution to design Shared Experiences with Augmented Reality and Internet of Things (ShARed IoT) devices. Our system enables users to interact with each other and their electro-mechanical prototypes through AR. A Projective Interview study with 9 UX experts, followed by an initial study with middle school students, and a field study with 13 users were conducted. Our results show ShARed IoT as a system enables unique shared AR-IoT experiences for both novices and expert users.

CCS Concepts: • **Human-centered computing** → **Open source software**; **User interface toolkits**.

Authors' addresses: Anonymous Author, Institution, Address, City, State, Postal Code, e-mailaddress; Anonymous Author, Institution, Address, City, State, Postal Code, e-mailaddress; Anonymous Author, Institution, Address, City, State, Postal Code, e-mailaddress.

0004-5411/2020/10-ART111 $15.00
https://doi.org/10.1145/1122445.1122456

Additional Key Words and Phrases: Maker Culture, Augmented Reality, Shared AR, Internet of Things

ACM Reference Format:
Anonymous Author, Anonymous Author, and Anonymous Author. 2020. ShARed IoT: Designing Shared Experiences in Co-Located Spaces with Augmented Reality and Internet of Things Devices. *J. ACM* 37, 4, Article 111 (October 2020), 31 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

Humans naturally yearn to socialize with others in a way that makes us feel connected to one another, whether it is in person, via social networks, or through video games. This is proven by the multitude of research conducted on the way that humans socialize with one another [9, 20], with other animals [7], and even with robots or other technology [8]. Collaborative technology acts as an interface between people and puts emphasis on high social presence. This technology has shown evidence to be more efficient with higher participant satisfaction and is often perceived to be more useful [31]. With the emergence of new Augmented Reality (AR) technology in mobile devices and Head-Mounted Displays (HMD), there is a natural progression to create shared AR experiences among multiple users, and to study how we interact socially therein.

AR occupies a unique space – somewhere in the middle on the spectrum of reality, with the real world on one end and the virtual on the other. This position of AR enables it to explore some unique interaction modalities between virtual content and physical objects in the real world [44]. Commercially available AR applications such as Pokemon GO™ [37] have proven the existence of massive support for collaborative AR applications. The current version of this AR application enables users to view and interact with other trainers' buddy Pokemon and catch other wild Pokemon in virtual AR instances [24].

The virtual-physical interaction enabled by AR systems allow for a better understanding of the world around us as never seen before [4]. Many prior works in this space have studied these interactions and fabricated devices for users to manipulate, which work in tandem with their AR applications [78, 81, 84, 85], while other works allow for some level of customization to their physical devices [23, 53, 54].

The advent of the "Maker Movement" has given rise to a culture that puts emphasis on innovating, hands-on crafting, and designing [42]. Peppler and Bender describe the Maker Movement as a "*do-it-yourself (DIY) (or do-it-with-others) mindset that brings together individuals around a range of activities, including textile craft, robotics, cooking, woodcrafts, electronics, digital fabrication, mechanical repair, or creation — in short, making nearly anything,*" [59]. These examples provided the opportunity for Makers to design and create their own devices that operate in the Internet of Things (IoT). New computing chips, such as those developed by Espressif [17, 18], help make this possible by turning regular electronics into Wi-Fi- or Bluetooth-enabled systems that share information across networks to desktop computers, tablets, and cell phones for further processing. In essence, they create a new dimension for Makers to explore for industrial, practical, and educational contexts.

Existing research on shared AR experiences shows that social interactions occur naturally and translate well to AR-based applications. Poretski, et. al. showed that *Design for Control* and *Regulation* are two requirements that address their participants' concerns for socially acceptable shared AR experiences [62]. Social Apps such as Octi [56], SketchAR [70], Snaappy [71], and WallaMe [82] give users the ability to superimpose AR drawings, graffiti, and images onto physical surfaces around the world and share them with others. All of these works show the breadth of capabilities that AR affords for multiple users; however, researchers are still questioning how collaborative AR interfaces should be designed and used to shape the way we interact with one another [43]. CollabAR [83] provided insight to this question with their study on co-located group collaboration and presented five design recommendations for improving user experiences with co-located collaborative AR applications. Inspired by the design recommendations and prior work, we investigate shared AR and IoT experiences where multiple users can build DIY IoT devices that can be controlled by and interact with AR content. Simply put: *past work in this space has provided significant evidence of the need for technology such as collaborative AR, Custom IoT development and Do-It-Yourself (DIY) based systems, individually. Whereas, we explore the intersection of these technologies.* To this end, we developed ShARed IoT, a collaborative AR platform for co-located spaces that enables custom IoT development through DIY protocol. We have explored its potential application in a variety of real world use cases such as education, interactive workshops, and story telling.

To obtain a guided understanding of how shared AR experiences can be enhanced by the design of customized IoT devices, we conducted a Projective Interview study, which motivated us to design the system that utilizes both collaborative AR and IoT devices. We also followed up the walk through with a set of user evaluations to study the feasibility and usability of this system on 13 users, which provided insight into how users felt about the system.

To this end, we present our experiences with Designing Shared Experiences with Augmented Reality and Internet of Things Devices (ShARed IoT). The following are our main contributions with our analysis:

(1) An AR-IoT system that enables users to design and program IoT devices to be used and controlled among multiple users for a shared AR-IoT experiences,
(2) A web-based block programming system that allows users to program their DIY IoT devices, along-side a visual simulator for verification.
(3) A preliminary Projective Interview, an initial study with Middle School students, and a final user study exploring the usability of the system, which indicates how ShARed IoT can be applied in the real world.

2 RELATED WORK

Our research builds on prior work that focuses on creating technology that allows for virtual content to interact with physical devices, technology that makes collaborative tasks easier and more engaging, and technology that aims to create shared AR experiences in co-located spaces.

2.1 Virtual-Physical Interaction

Augmented Reality superimposes virtual content over the physical world. Several prior works in this space have aimed to leverage the interactions between virtual content and physical objects. Smartphone applications such as Google's 3D animals [36] and Snapchat [72] filters overlay virtual content on the user's environment using smartphone cameras and allows users to interact with the virtual objects, while the physical environment remains passive in the background. We have explored ShARed IoT, which enables virtual objects to interact with physical IoT devices built by users, while also enabling a collaborative platform.

Some researchers have explored the use of handheld projectors such as in Motionbeam [84] and HideOut [85] to shift the interaction modality from display screens to physical surfaces, thus allowing for interaction with a dynamic physical environment. Motionbeam uses infrared tags while HideOut relies on images printed in invisible ink to enable such virtual-physical interactions. Project Zanzibar [80], on the other hand, makes use of a tangible mat interface to track physical objects using Near Field Communication (NFC) to create such interactions. While these works transform large physical surfaces into digital canvases, they require specialized hardware for deployment instead of relying on widely used AR devices and off the shelve hardware. ShARed IoT has been designed to be deployed on smartphones (or tablets) as they still remain the most widely

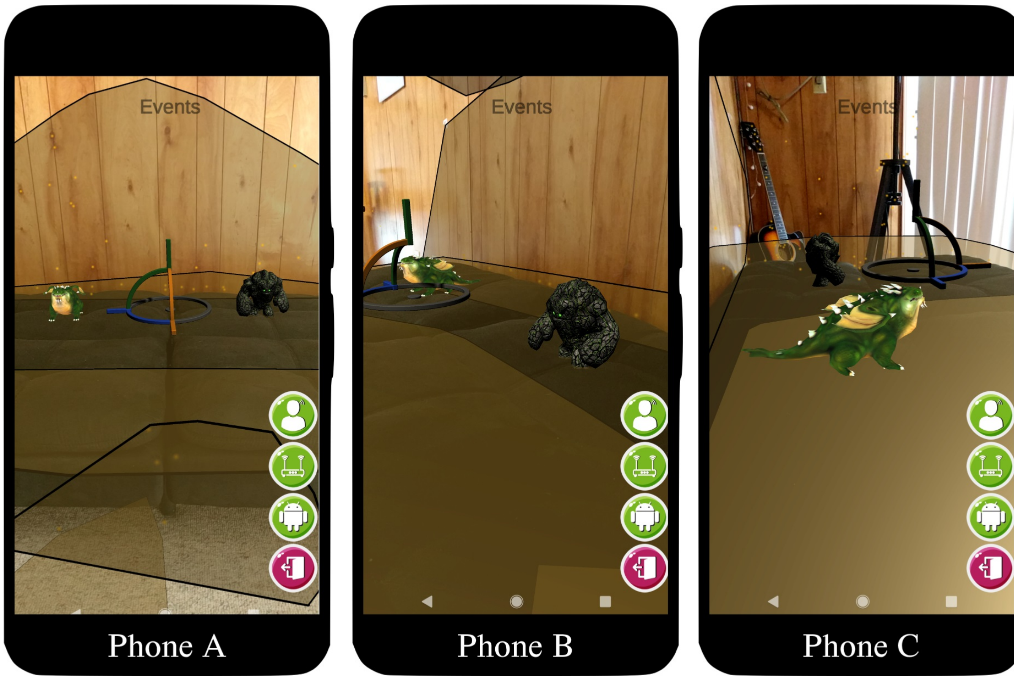

Figure 2: *Three separate views of shared experience with synchronized locations for AR Content: looking from the front (A), looking from the right side (B), and looking from the left side (C).*

used medium for deploying AR applications today. Due to their accessibility and ease of use [32], they provide vastly greater interactivity while still allowing collaborations among users. ShARed IoT also empowers users by enabling them to program and create their own AR content (authoring own content), instead of focusing purely on AR delivery.

Recent advances in computer vision, robotics, electronics and fabrication have transformed physical objects in the environment from being mere passive objects to active input media for the system. Works such as ARchitect [46] generate a virtual world that adapts to the physical environment and suggests proxies for physical components, using vision, to enable interactions. Work such as ConductAR [53] measures electrical properties of an augmented sketch of a circuit. Coupled Clay [57] makes use of a robotic arm to manipulate physical objects by receiving commands from a remote virtual space. While these works advance the concept of using tangible objects as input media, they don't provide any active feedback to the user nor explore collaboration between users. ShARed IoT tries to address these limitations by exploring the possibility of using custom IoT devices.

Creating AR content still remains to be limited to experts but projects such as ProtoAR [54] and Pronto [44] simplify this task by enabling users to translate physical content to AR by simply taking pictures or creating sketches, annotations, or video recording 3D clay models. In contrast, ShARed IoT addresses this by enabling users to create AR events and correspondingly reactive IoTed devices via a digital assets library and simple drag-and-drop interfaces. Furthermore, including smart IoTed devices in AR applications has enabled greater control over virtual-physical interactions, such as Scenariot [34] which uses a SLAM-based mobile AR system to create a spatial map of IoTed devices in the area and allows users to identify and interact with them. Recent work like StoryMakAR [23] has enabled interactions between virtual objects and physical programmable IoT devices. However, StoryMakAR has been designed only for a single user experience, to create stories by triggering a series of interactions between virtual and physical components. ShARed IoT has been created to leverage and explore these physical-virtual interactions between IoT devices and virtual content between multiple users to create a more engaging experience.

2.2 Collaborative Technologies

Current cloud-based applications such as Google Docs [29], Github [22] and Fusion 360 [3] allow multiple users to collaborate remotely on various assignments and tasks. In contrast, we define collaborative technologies as those that enable collaborative experiences in co-located spaces. Platforms that promote collaboration have also been implemented in applications that promote creativity. KidPad [33] is a shared digital canvas that allows kids to collaborate and create stories together using a desktop computer. Work such as Mobile Stories [19] make use of a special handheld hardware interface to enable kids to create stories by supporting collaboration and mobility. This system promotes creativity by allowing kids to build on each other's ideas to create stories. Similar aspects of collaborative creativity in product design have been explored in Co-3Deator [61], a collaborative 3D modeling platform. Maestro [14] explores collaborative technology for supervision of tasks and instruction delivery in a 3D modeling context. Prior work such as [64] and [2] discusses the effect of team productivity and cognitive processes of collaborative technology. While past work in this space has explored the advantages from only a collaborative environment perspective, such as Christie [11], Fowler et al. [21], and Short et al. [69], ShARed IoT allows participants to collaborate on tasks while also leveraging the advantages of virtual-physical interaction by enabling a AR-IoT interactivity.

2.3 Shared Augmented Reality Experiences

Mobile AR applications such as Pokemon GO^{TM}, WallaMe [82] and Snaappy [71] use inbuilt GPS to track users and render the AR content based on their geographical locations. Recent industrial AR applications have allowed users to view AR content in-situ, while being located remotely [63]. Similarly remote AR/VR applications have been explored in research by Loki [76]. With recent developments in AR hardware and software, users can now create a virtual avatar and collaborate remotely with others in a physical space with Spatial.io [41]. Although such shared AR experiences overcome geographical boundaries and closely represent in-person interactions, they don't provide the kind of virtual-physical interaction and DIY features that are akin to creative endeavours such as ideating, storytelling, and education. ShARed IoT addresses this challenge by providing a shared AR experience in a co-located space and features to create and program your own interactive IoT devices.

Transvision [65] allows co-located users to collaborate by projecting 3D objects on a table-top surface and viewing it via a hand-held display. This aids in improving engagement and participant satisfaction because collaborators can see the actions and gestures of their teammates, while still allowing them to communicate naturally. Shared AR experiences have found a wide range of applications from crime scene investigation [13] to authoring and peer discussion of hands-on STEM sessions [79]. Such experiences also vary in the scale of the environments from a table-top [65] to a large room [35] to even extending up to city scales [67]. Shared AR for co-located and isolated participants create two distinct kinds of experiences and have their advantages and limitations. ShARed IoT attempts to take advantage of co-located shared AR experiences to perform collaborative tasks, while still enabling virtual and physical object interaction.

2.4 Motivation & Design Goals

Based on the aforementioned prior works in this section, we found a unique gap across the hardware and software implementations of these works. AR-IoT interactions are a relatively under-explored research area. Before designing and developing the ShARed IoT system, we first wanted to learn how AR-IoT interactions are used today to motivate our development. As we mentioned, DIY culture is an important factor to consider, especially when using physical computing devices like Arduino [74], and Micro:bit [6]. The reason being is that these physical computing devices are generally used to create actuated machines with the various electronic components, physical structures, and programming. Selling them at a low cost helps increase accessibility, so using low-fidelity materials is ideal in some cases. However, other physical computing platforms such as VEX robotics [40], and LEGO Mindstorms/EV3 [30] use higher fidelity materials to accompany their physical computing devices, while still allowing users to modify those materials in typical DIY fashion. Our main hardware questions here were, *Are low fidelity materials better for an AR-IoT platform, or high fidelity materials?* and *Are the current physical computing solutions suitable for an AR-IoT platform?* Ultimately, we decided to use low fidelity materials in order to increase **accessibility** and **expression** in our users.

Finally, since our main demographic is youth and novices (although experts users should also be able to use the system), we found that many of the aforementioned physical computing solutions would yield a steep learning curve when combining both programming and electronics for novice users. We aimed to invoke Mitchell Resnick's principle of Low Floors with a solution that would reduce the barrier of entry for our user demographic. The Hummingbird Robotics kit [75] is a viable solution to do this; the problem is that there is still a dependency on some basic level of electronics knowledge that could present issues for novices. Thus, we sought to design our own physical computing device that is **plug-and-play** in order to help our novices focus on the computing aspects as an entry point to physical computing and not have to worry as much about the electronics.

As we mentioned, AR-IoT interactions are under-explored. We aim to study these interactions because separately, they are able to create amazing experiences for both novice and expert users alike. AR is beginning to become more mainstream, being used in commercial applications, as well as industry use-cases. The main consideration here is whether to use AR-enabled cell phones or head-mounted displays to enable our AR-IoT experiences. In the end, since accessibility is a main priority of ours, we decided to use cell phone AR for the project. Thus, we were moved to combine our IoT devices with AR content to generate a unique and engaging experience for our users. In the next section, we describe the ShARed IoT system's hardware and software implementation in detail.

3 SYSTEM OVERVIEW

In this section, we will describe the key components of the ShARed IoT system: AR and IoT communication across devices, our custom hardware devices, and our software system.

3.1 Hardware

The electronic subsystem of ShARed IoT was designed to provide a set of electronic devices that add a creative physical element to our collaborative, multi-user, AR-IoT experience. Electronic toolkits that are available on the market often require a basic understanding of electrical concepts and component functionality, all whilst presenting no opportunities to supplement an AR experience [30]. Keeping this in mind, we aligned our design goals to address this challenge and designed an IoT Printed

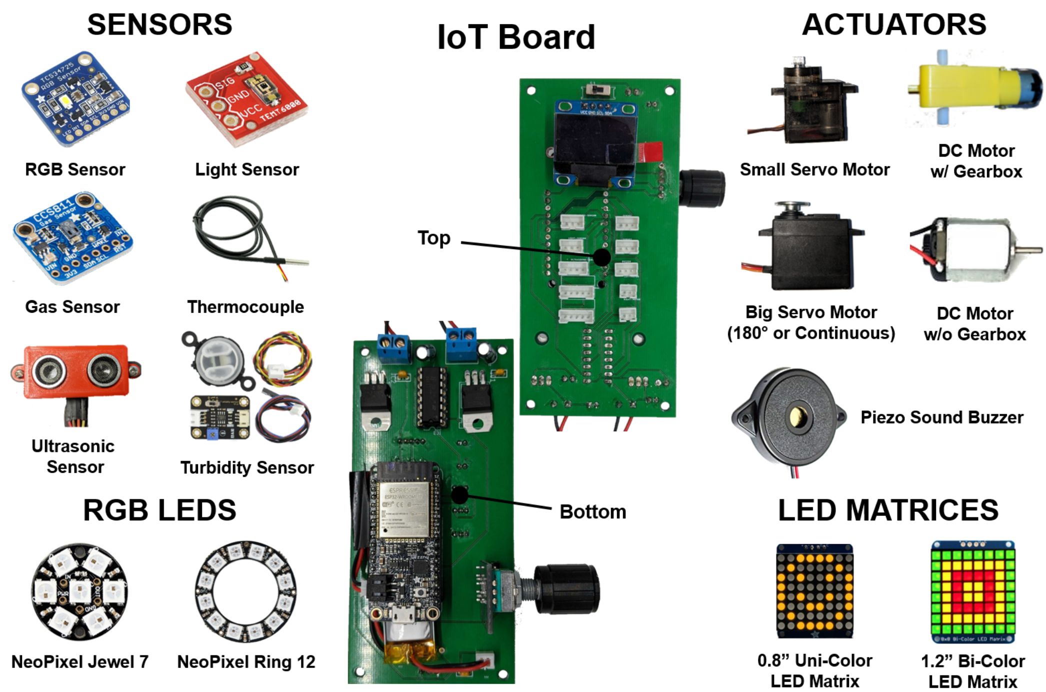

Figure 3: *Our Electronics Repository, with 6 sensors and 2 RGB LEDs on the left, 5 actuators and 2 LED matrices on the right, and both sides of our custom-made IoT PCB in the center.*

Circuit Board (PCB) that interfaces with other secondary electronic devices in a simple, plug-and-play manner. In order to facilitate a seamless wireless AR experience, an Arduino-core based Wi-Fi capable micro-controller unit (MCU) [39] was incorporated into our IoT PCB along with several ports to provide in/output capabilities. Moreover, several electronic components that are commonly implemented in maker-based projects were selected and used when designing and building the PCB and our initial electronics repository (see Figure 3). Maker devices currently in the market such as the Micro:bit and Adafruit Circuit Playground [6, 38] implement dot matrices and LEDs directly on their PCB so as to allow for easy and simple visual indicators. LED Matrices and RGB LED devices were included in our repository to allow for similar functionality, with the added benefit of multiple colors. Several actuators were also chosen to allow the user to add motion and sound to their devices. In an attempt to provide sensory conditional control, Ultrasonic sensors were initially added to our repository. However, due to needing to detect a wide array of changes caused by chemicals in our preliminary user study (please refer to Section 4.2 for more details), several more sensors were included in our initial electronics repository. Future efforts made towards the expandability of the repository will attempt to provide users with a device template that they can use to add more components to the catalog.

While developing our IoT PCB, several of Gestalt's principles of perceptual organization [12] were utilized to ensure that PCB components and header ports were placed in a manner that made them intuitive to use. This decision was made to help mitigate a common issue that we experienced in the other kits we explored, like Micro:bit and the Hummingbird Robotics kit [6, 75]. We felt that overly complicated wiring diagrams were abundant in kits meant to teach programming and design concepts. Our IoT PCB provides users with 3 input, 5 output and 2 I^2C ports. Actuators, LEDs and other output devices interface with the 5 output ports, whereas the sensory devices connect to the 3 input ports. The presence of two ports that use the I^{2}C protocol allows for a multitude of both modern input and output devices to be controlled effectively by the MCU. These ports help facilitate compatibility with future sensors which in turn supports our goal of allowing the user to expand the provided electronics repository.

Due to having a variety of sensors, actuators and LEDs, work was put in towards establishing an efficient power distribution network on the IoT PCB such that it utilized three unique power sources to cope with varying load. The power distribution network balances load between devices plugged in to the I/O ports and MCU on the PCB using a single 3.7-volt Lithium-Polymer battery and two 9-volt Lithium-Ion batteries.

3.2 Software Implementation

Augmented Reality has a natural link between virtual and physical realities by nature. A system that is built to make use of this powerful property must contain a link that automatically connects the AR content to the physical devices (geometric, digital/informational, and positional data). Novice users may not have experience in designing IoT devices due to potential limitations in programming prowess, content creation, and an understanding of wireless communication protocol. For this purpose, we designed two applications that help make the task of programming a customized IoT device, generating AR content, and creating interactions between the two as easy as possible.

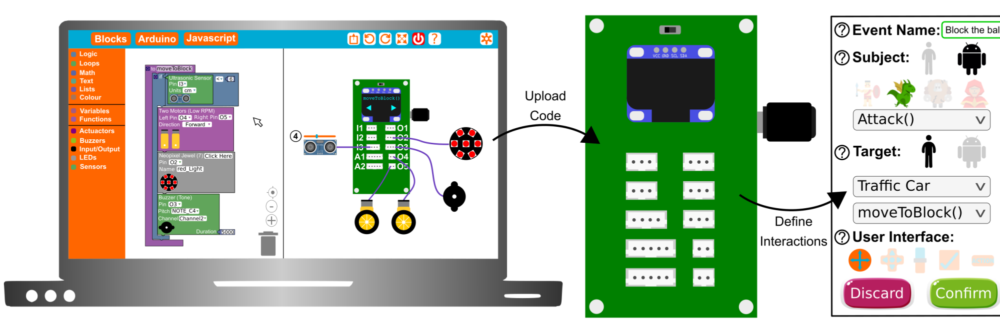

Figure 4: *Interaction Flowchart (from left to right): Users generate code for their IoT devices using our block-based programming environment. Users can upload their code to the IoT PCB and the resulting device data is imported to our GUI for further processing. Using the GUI, events can be created that allow interactions between AR and IoT content.*

3.2.1 IoT Maker: The first of our solutions, IoT Maker, is a web application that derives from the Google Blockly Application Programming Interface [47]. Users can drag and drop small blocks of code to quickly create large methods for their devices to perform. We chose to use Blockly because studies show that visual programming has several benefits to end-users, including the lack of professional programming skills that are necessary for use, flexibility, and its ability to output syntactically correct code on the behalf of the user [51, 58]. Our blocks are compatible with the various libraries that are necessary to operate the secondary devices in our Electronics Repository (see Figures 3 and 4) and give the user a wide range of functionality for their IoT devices.

Another benefit of incorporating a block-based programming interface to create syntactically correct code is that it reduces the amount of time spent programming. This affords users more time to create design iterations and make the functionality of the device(s) more complex. What is more, IoT Maker features a live-action simulator so users can have a visual representation of their device to iron out any potential issues before compilation. This is imperative for the users to ensure their devices are operating as intended when they move on to the next step in the IoT creation process. Previous research done on the effects of including live simulation in programming environments for novice users states that while existing live programming experiences are not very usable due to challenges in the realms of UI, latency and interactivity, the experience is compelling to users and that future work in this field will be worth the effort [48]. Once users are satisfied with their code, they can submit their device to our database (See 3.2.2) for use in event creation (See 3.2.3). Users will also receive their PCB code which can immediately be uploaded to our board.

3.2.2 Database: The main link between IoT Maker and our Event creation system is a NoSQL cloud-based database provided by Google's Firebase product [25]. The database allows us to store information about the device's name, who created it, and the functions that were created for it. In the event that a user wants to re-use a device for different experiences, it is helpful to retain all of their devices in the cloud. IoT Maker allows the user to create and edit their saved devices, and that data is able to be cycled into the next step of the system.

3.2.3 IntARact: As mentioned before, Augmented Reality is dual in nature; it has a natural balance between both the physical and virtual realities, which can be exploited in many ways. A typical problem in HCI is that computing devices are not adept at understanding our exact thoughts and ideas, but can be made to execute those ideas given the proper instructions. We developed an interaction-based Graphical User Interface (GUI), titled IntARact, as a part of the mobile application to extract the IoT Device names and function data from Firebase for further processing. In this application, the user can choose from a catalog of AR content, pre-designed IoT devices, or from their own customized IoT devices to control. These custom devices are auto-populated from the aforementioned database when the user loads up the app and chooses their ID. Each interaction is thought of as an "Event," which contains a set of information related to the type of interaction the user wants to create. (1) The event name provides the user with a short description of the event. (2) The subject and target are AR or IoT content that any user can assume control over when collaborating. The chosen content will perform an action selected by the user underneath its name or image (see Figure 4). (3) Lastly, the UI control scheme denotes various input modalities that are available for users to move, operate, and manipulate their AR and IoT content. These events are saved in the JSON format for use in the main system application, detailed in Section 3.4.

3.3 System Use Cases

At its core, the system allows users to explore how Augmented Reality (AR) can interact with physical microcontrollers however the user chooses. For example, say a user wants to create a microcontroller that acts as a powerful enemy for a set of AR characters.

The user will begin with IoT Maker, to design their IoT device. They can use servos to act as arms to perform an attack, wheels to move around, and an LED matrix to display facial expressions. All of the functions are then programmed by the user using the block programming interface. How many degrees do you want the servos to rotate? How far can the wheels move at a time? How are you going to animate the LEDs? What will move when the enemy gets hit/dies? These are all questions the user can address by programming each action into separate functions with the block interface.

Once the design has been finalized and tested with the simulation tool, the user can move to the mobile app. As it stands, the user has an IoT device that has numerous, separate, pre-programmed functions that have no way to be invoked. IntARact allows the users to configure how a device is to be interacted with. In a broader sense, a device can interact with an AR character, or another device. Likewise, an AR character can interact with another AR character, or a device. In this case, the user is setting up the scene for their battle between one device and a variable amount of AR characters (with predefined animations). Here are some sample scenarios for interactions that are relevant for this example: (1) If the IoT Device comes in contact with an AR character, we want the IoT Device to use its arm attack function, while the targeted AR character does a hurt animation. (2) If an AR character uses a weapon animation to attack the hitbox of the IoT device, then the device should run a function that shows pain. (3) An AR character can use a healing animation to trigger a different AR character's respawn animation. (4) In the event you had multiple of these enemies, you could have one IoT trigger a blocking function, which in turn could trigger the blocking function of the other IoT. The format for these interactions in IntARact follow a subject-target pattern, as shown in Figure 4. These interactions are then stored locally so that the user can load them into the system at any time, in the event that they want to explore different outcomes with different groups of people.

Finally, the user is able to get a group of people together to begin a shared experience. Controls on the phone allow users to control either an IoT Device or an AR character. To ensure synchronization of all devices on the network, only one interaction can be triggered at a time. which is denoted by text at the top of the screen, so participants know which characters are involved. A scenario depicting an example use case of the system is detailed in Figure 5.

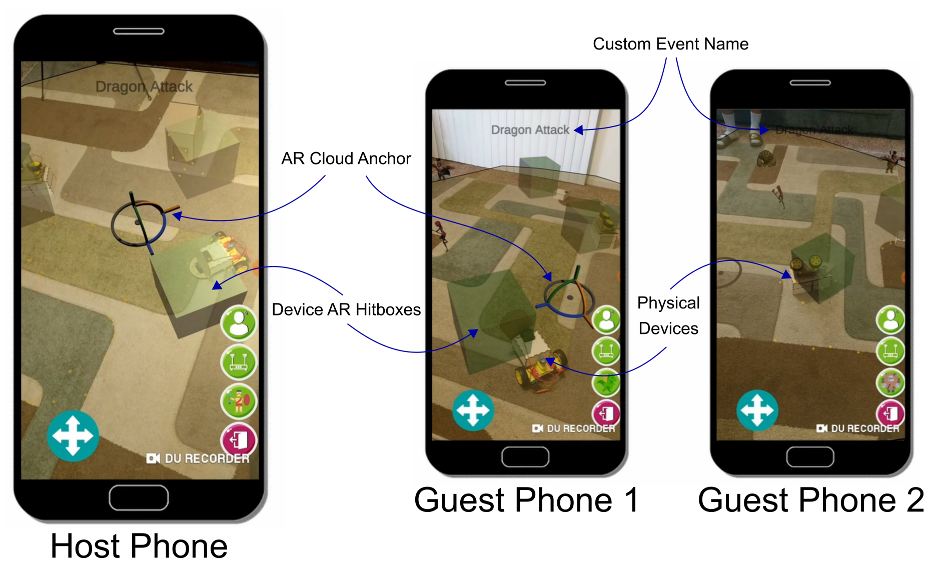

Figure 5: *System use case scenario involving 1 host phone and 2 guest phones. The interaction selected involves the AR Dragon attacking the physical car device upon coming into contact with its hitbox. Guest 1 has control over the AR Dragon, while the others control different AR characters.*

3.4 AR-IoT Communication Across Devices

The AR app is built utilizing Unity's AR Foundation Framework meant for multi-platform Augmented Reality applications [77]. This framework allows for the app to run natively on a multitude of different mobile Operating Systems, which increases accessibility for anyone wanting to get involved in a shared experience. It also allows for easy integration of plane detection by generating point clouds that plot an area dynamically as the phone camera moves around the room. By utilizing rudimentary AR utilities handled by Unity and AR Foundation, the next step was to create a multiplayer network for users to be able to generate their own shared experiences using AR and IoT content.

We achieve our multiplayer capabilities by using Photon, which is a free engine that gives developers access to cross-platform servers that synchronize and share information through the cloud [60]. We were able to use Photon to create a lobby for anyone wanting to use the ShARed IoT System. Users have the option to create their own room for others to join, or join a pre-existing room that someone else has created. These rooms enable the transfer of AR and IoT data between connected phones that are inside of a specific room. Each data message is able to be buffered in the server so people who join a room after messages have already been sent can still receive all required messages in the original order they were sent in. Buffered messages are the way that our rooms are able to "store" information.

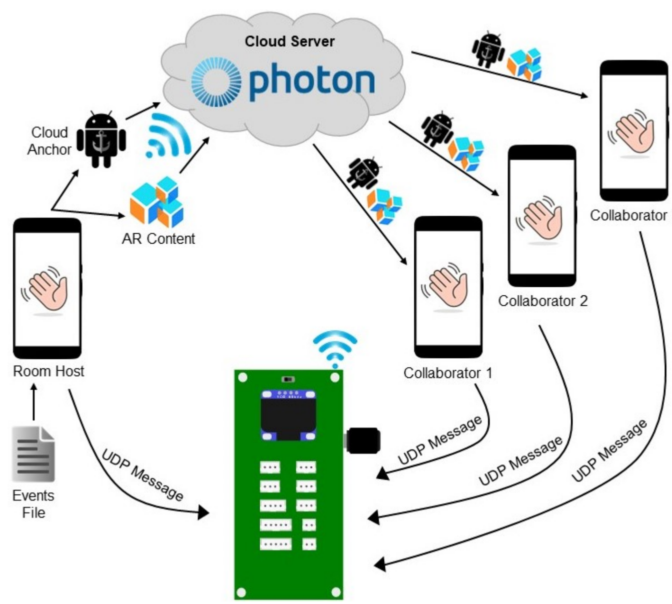

Figure 6: *The ShARed IoT system architecture for communication between devices: (1) Room Host loads their custom experience from a file on their phone and places the Cloud Anchor and AR content on the screen. (2) Once the host is finished, they send positional data about the Cloud Anchor and surrounding AR content to the rest of the users in the Photon room. (3) All collaborators in the room receive the data and spawn the content in the correct location and rotation. (4) Any user can now interact with IoT devices using UDP communication over WiFi.*

However, for this shared AR experience to be truly authentic, our AR content has to be displayed in a manner which caters to phones located in various parts of the physical space set for that experience. Since users can create physical IoT devices that have a fixed position in the real world, the AR content on each phone must be synchronized to display in the same location. To achieve this, we used some extensions from Google's ARCore SDK, which enables the use of Cloud Anchors (CA) [28]. CAs are AR objects detect distinct features in a physical space to collectively produce a global coordinate system. Having a CA be the "origin" point of the coordinate space makes multiplayer synchronization very simple; the room's host must first place a CA before setting up their experience so that the initial buffered message collaborators receive when joining the room is the real-world location of the CA. Once the phones in the room "resolve" the CA, it gives their phone the local coordinate system that will be used when spawning AR content. This in turn ensures that all AR content has the same location, rotation, and scale to the CA and the IoT devices. After the initial CA resolution, the anchor goes through a process of resolving every ten seconds in case there are brief tracking issues or camera occlusion. This is also necessary to correct the aforementioned positional errors that may occur.

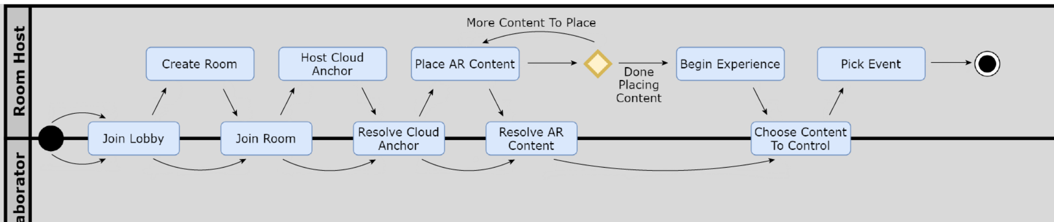

Figure 7: *A flow of events for a participant in the ShARed IoT System*

4 INITIAL STUDIES

Our initial exploration of this system was to gain insight to how users would expect to use a system like this to create shared experiences among multiple people. We conducted a Project Interview study with 9 experts in user experience (UX) development and research to gain this insight. Additionally, a preliminary usability study was conducted with a group of 8th grade science students at a middle school.

4.1 Projective Interview

According to Rieman, et. al, the cognitive walkthrough study technique evaluates the design of a user's experience with the system interface(s) and describes HCI in four steps: (1) the users first define a problem to be solved, then (2) they search the interface for solutions to that problem, (3) select the action they deem appropriate, and finally (4) perform that action and evaluate the evidence of progress toward the goal [66]. Likewise, Rick Spencer presented a modified process for a streamlined Cognitive Walkthrough in which there were four similar steps to conducting such studies [73].

Using these proposed methodologies, we adapted our cognitive walkthrough study, which was conducted on 9 UX experts in various fields[1]. One limitation of the study was that it was conducted virtually with the experts not having access to the physical hardware and the software of the system. Since the study is not a true Cognitive Walkthrough where the participants use the technology, we refer to this study as **Projective Interviewing**, which was inspired by the Cognitive Walkthrough method. Exact study procedures are given in Section 4.1.1. We define an "expert" to be someone who has two or more years of professional or academic knowledge creating experiences for users in *Augmented Reality*, *IoT Development*, *Electronics*, and/or *Workshop/Curriculum Development for Youth*. The study started with a pre-survey given to collect relevant demographic data from the experts, as well as to administer a proficiency scale in their field (adapted from the internet self-efficacy scale given by Eastin, et. al [15]). The crux of the study was spent by giving the experts an overview of the capabilities of the system without divulging the exact functionalities that the system possesses, asking interview questions related to our three Representative Tasks, a short video of the system and it's various features, and finishing with a post-study survey where they were asked to comment on their system expectations vs. how the system actually functions.

4.1.1 Representative Tasks: As stated by both Rieman and Spencer, a cognitive walkthrough study should incorporate some tasks that represent actions to be performed with the system. Our representative tasks are defined as follows: (1) narrating a story that contains interactions between AR and IoT content (2) curating an interactive workshop for participants to use the ShARed IoT

[1]In light of COVID-19, we conducted remote interviews with our experts to minimize contact between us. The preliminary study was conducted before local schools were closed.

system to complete some task(s), and (3) crafting a lesson plan for students with specific learning outcomes using the ShARed IoT system.

As mentioned earlier, this study consisted of interviewing 9 experts in various fields. Each interview lasted approximately an hour and was conducted virtually via Cisco WebEx™ to keep the researchers and experts safe. After completing the pre-survey, the interview started by asking our three grand tour questions (See Appendix B: Interview Questions for UX Experts for all interview questions). Following these questions, we introduced them to Representative Task 1 with a short description and an example of the Task, and then asked the next four questions, which are related to the Tasks. Once all questions for that Task were answered, we introduced the next Representative Task to them and repeated this until all 13 interview questions were answered and the interview was completed. Next, we played a short video for the experts to watch, which showed how a user would complete each of the Representative Tasks using the ShARed IoT system. While the video played, the researchers spoke to the experts to explain step-by-step what was happening and answered questions that the experts had about the system. We decided to wait until the end to show the video so as to not bias the experts' answers by having them see the system capabilities while thinking about the Representative Tasks. Finally, we asked the experts to complete the post-study survey before logging off.

4.2 Preliminary Usability Study with Middle School Students

Since some of our Representative Tasks can involve youth between the ages of 13 and 18 years, we decided to conduct this preliminary study on students in the lower end of the spectrum. The first step to this project is to conduct pre-study interviews with the 8^{th} grade science teachers at the middle school. The scope of this interview was to elicit criteria for integrating this system into an 8^{th} grade science curriculum (a copy of the interview questions can be found in Interview Questions for Teacher). Naturally, the teachers will have the best perspective on how the students learn, and how they might benefit from our system in the classroom due to their years of experience and rapport with their students.

Working with the teachers, we developed a lesson plan for the students to conduct an in-class experiment in groups of 3-4. The study was conducted with the students in only one of the teacher's classes, with a total of 123 students overall. There were six sections of our teacher's science class, with approximately 20 students per class. It is worth noting that during the planning phase of the experiment, the teacher found that bringing the cell phones into the classroom for the students to use could cause major distractions and would disrupt her "No Cell Phone" classroom policy. However, we felt that it would be a strong example of the flexibility of the system to proceed with the study using an abbreviated study methodology that was still engaging for the students. The study was conducted in 3 parts:

(1) Students received a brief introduction to the system through a structured activity that gave the students control over various features of the system. Students learned how to connect the secondary electronic devices to the IoT PCB and collect sensor data,
(2) Students completed a lab assignment in class. The objective of the lab was to learn *How to Tell if There Was Really a Chemical Reaction*. There are several ways to tell if a chemical reaction has occurred: (a) change in color, (b) emission of light, (c) change in temperature, (d) emission of gas, and (e) formation of a precipitate. Each chemical reaction required a different sensor to be used, sensory data to be collected, and the type of chemical reaction to be recorded into the lab manual (a copy of the lab manual can be found in the supplementary materials).
(3) A live demonstration of the system capabilities was conducted by the researchers. The cell phone screen was broadcast to the classroom projector and the students were able to bear

witness to the system capabilities by helping the researcher advance through events by providing answers found from the laboratory experiment.

4.3 Data Analysis

While designing the study, we also took care to incorporate each of our representative tasks so as to ensure an accurate reflection of feedback received from our expert evaluators. We developed a lesson plan for the students with clear learning outcomes (*How to Tell if There Was Really a Chemical Reaction*), an interactive workshop that included the use of the IoT PCB to collect sensor data from the experiment, and a live demonstration in the form of a story where students had to give the researchers the correct answers to trigger the virtual-physical interactions. In the subsequent sections, we discuss the findings from this study in further detail.

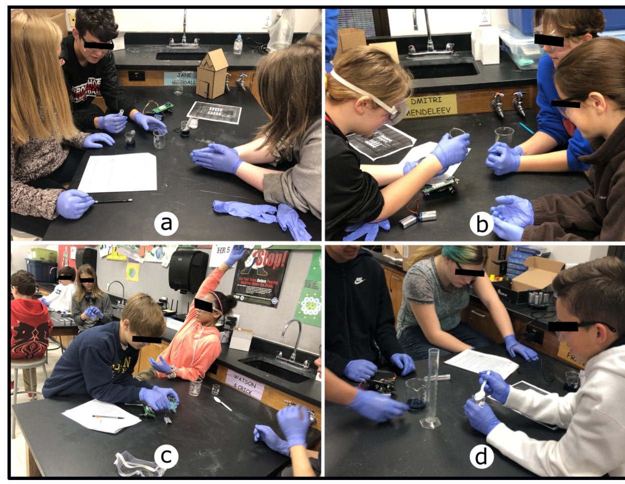

Figure 8: *Students at their lab tables (a,b) working on their lab assignment during our preliminary usability study, (c) asking questions about the assignment, and (d) creating a chemical reaction.*

In order to analyze the data from our projective interview study, we use a mixture of both qualitative and quantitative analysis methods. Pre- and post-survey questions were administered using both a 5-point and 7-point Likert scale. Likewise, our preliminary study post-survey included a plethora of 5-point Likert scale questions. Additionally, we adopt categorical coding practices that are given in [49] to analyze the interview answers from our experts, as well as several answers to open-ended questions given to us by students in our preliminary study.

4.4 Expert Study Results

In this section, we will discuss the results from both our Projective Interview study, as well as our preliminary usability study. We report all Likert-scale questions with the mean (m), standard deviation (σ) and variance (V). All participant names are replaced by pseudonyms to protect participant identity.

4.4.1 Expert Evaluators: Our experts had a wide range of experience in the knowledge areas mentioned in the previous section. Each of them offered unique perspectives to how they would approach each of the questions and representative tasks posed during the interview. Figure 9 gives an overview of the expertise of the evaluators. Among the 9 experts (2 female), majority of interviewees defined themselves as experts in AR development, IoT development or electronic development. We had one person identify as an expert in development of educational youth workshops.

The exact questionnaire can be found under Appendix B. We have summarized and clustered the experts responses into the following categories. Some experts came up with multiple suggestions, all of which have been documented. Hence, the total number of choice doesn't always sum up to 9.

4.4.2 AR Input Suggestions: The Expert users were asked on their preferred choice of input modality, for an AR system they would be developing to accomplish the representative tasks (Section

4.1.1). Most experts (N = 7) expressed a need for a What You See Is What You Get (WYSIWYG) [68] based input modality, while a few (N = 3) recommended a voice based input modality to capture the user intent. There was one mention each for a hardware-based device such as an IMU, or a haptic device and Visual Programming. Since ShARed IoT was indeed a WYSIWYG based system, most expert users rated the system to match their expectations (N = 3) or Exceed expectations (N = 6).

4.4.3 IoT Input Suggestions: Several of the IoT device input methods suggested by our experts involved methods that were beyond what devices such as a touchscreen smart phones are capable of, such as haptic feedback devices. The use of the Inertial Measurement Unit (IMU) present in cellphones was recommended to facilitate physical shake-based inputs. Furthermore, the inclusion of more natural and intuitive forms of hands-free input control, such as voice commands, was advocated by our experts. In addition to the focus on simplicity in input methods, the ability to trigger set sequences of actions through logic nodes was proposed.

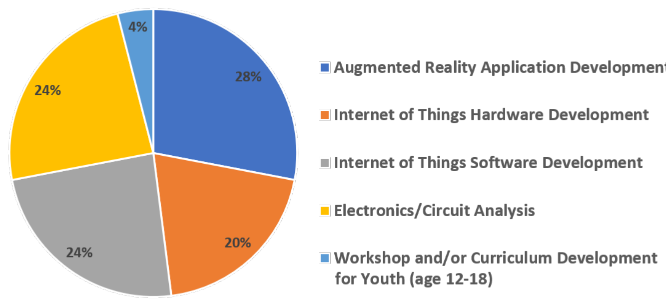

Figure 9: *Breakdown of our interviewee's expertise. Several of our experts were proficient in more than one area.*

4.4.4 Design of AR and IoT Content: Most expert users (N = 7) preferred some form of AR library containing a set of digital assets, that the users could simply drag and drop into the environment, which could be interacted with for AR content creation. Some (N = 2) even wanted these digital assets in the library to be customizable. Others (N = 4) suggested some form of annotation tool to render and create virtual assets and content. One user recommended that the environment and its assets be scanned. ShARed IoT does possess a drag-and-drop library for inputting AR assets into a scene. Thus ShARed IoT received a high rating (N = 7) with users rating the system to exceed expectation and (N = 3) users rating Far exceeded expectation.

4.4.5 IoT Device Design & Fabrication: One of the main themes that we extracted from our experts was regarding how easy it was to use the available secondary devices with the IoT PCB. Many of our experts stressed the importance of programming the custom IoT devices to be as easy and accessible as possible, so that it may not detract from the overall experience. Moreover, the importance of having a software toolkit that helps guide users along the design process of creating their IoT device was stressed. In previous versions of IoT Maker, we included only the block programming environment and found it to be helpful when asking novices to program, but it still made the IoT creation process difficult because novices aren't familiar with how the electronics operate and the subtle nuances that go along with programming them. **The IoT Maker live programming environment was designed with these suggestions in mind.** IoT Maker helps make this process easier because it gives our users feedback on how their devices function before they upload the code. An added bonus is that you don't actually need the physical hardware in order to program with and use IoT Maker. These modifications address both concerns of usability and accessibility that our experts brought to our attention, and align well with our initial design goals (see Section 2.3)

4.4.6 Task Collaboration: User's perspective and ability to control different components in the AR scene have a direct impact on the collaborative potential of the participants. Most experts (N=8) preferred that each participant be able to view the scene from their own perspective as designed in ShARed IoT. Experts shared many different opinions when asked about the control of the AR and IoT devices. Some of them highlighted the conflicting situations that may occur when multiple participants attempt to control the same device or virtual character, while others were concerned about scenarios when a user accidentally sends out a erroneous command such as deleting a component. In conclusion, an ideal system should allow one or more of the following three types of control:

(1) **Hierarchical:** one master participant has control of higher level functions while other participants have control of lower level functions,
(2) **Transferable:** participants can transfer control among each other, and
(3) **Distributed:** participants strictly control their own set of components.

ShARed IoT allows the host to do the initial set-up of the devices while allowing participants to choose and control the IoT devices and AR characters sequentially.

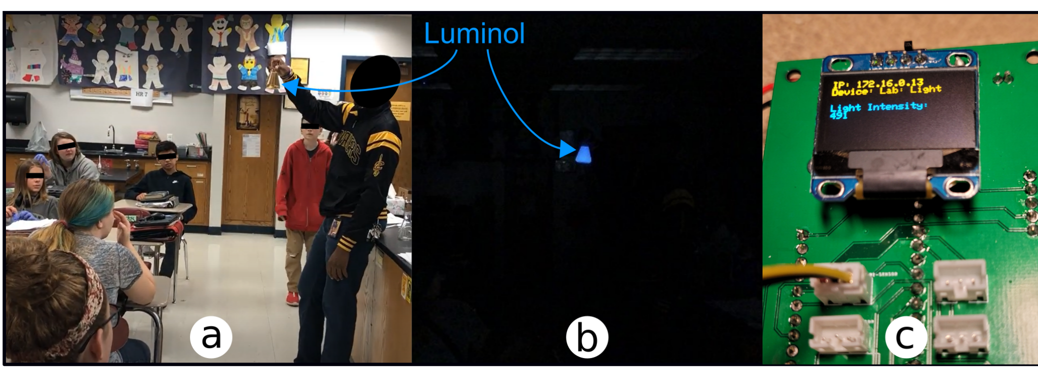

Figure 10: *(a) The students getting a demonstration of a chemical called Luminol (b), which produces a bright, blue light as its chemical reaction. (c) The sensor values are displayed on the screen of the IoT PCB while it is in Laboratory Mode.*

4.5 Middle School Study Results

The data was supplied from a sample size of N=123 students aged 12-13 (Male=51, Female=62, Unspecified=10). Of all the students, 58 had experience using AR apps in the past and 65 did not. The students were asked to fill a post-study questionnaire, which contained a mixture of Likert-scale questions, as well as some open-ended questions. When asked if they would like to use the system frequently, 67 of the students responded positively (m=3.439, σ=1.1344, V=1.287). More positive answers were primarily given to two other questions regarding the ease of use of the system (m=4.024, σ=0.888, V=0.788) and how easy it is to learn to use the system (m=4.024, σ=1.04, V=1.081). However, there were mixed reviews from students when asked if they needed to learn a lot before they could use the system (m=2.764, σ=1.25, V=1.5623). Since the students were primarily using the IoT PCB, we believe this could be because of connectivity issues between the PCB and the sensors. There were a few times where researchers would have to switch the PCB that groups were using so that the malfunctioning PCB could be repaired. More care will be taken to ensure proper connections between secondary devices to limit the frustration experienced by students.

Overall, we found that our participants enjoyed using the IoT PCB to complete their lab assignment. In particular, students commented on how much fun they had in addition to the Likert scale

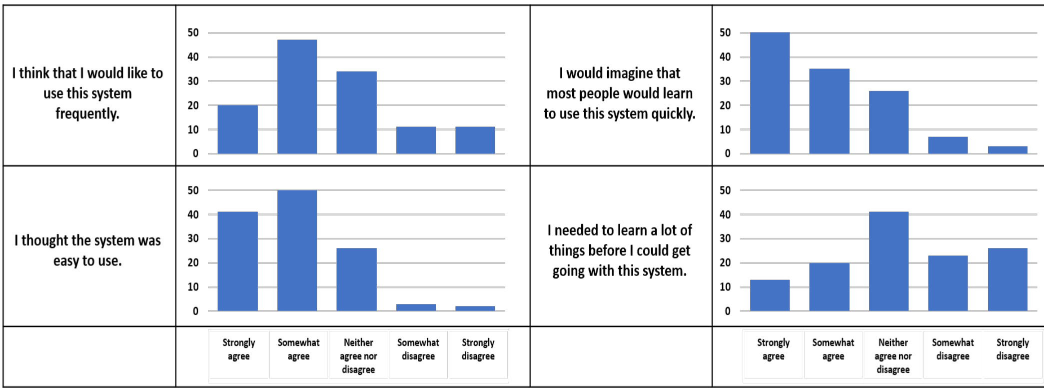

Figure 11: *Survey data taken from the middle school students during our preliminary usability study (N=123).*

questions. When asked what they liked most about the lab assignment, several students like John (Male, age=13) wrote comments related to the group work being the best part; whereas, Sarah (Female, age=13) stated, "*It was very different to use something like a [IoT PCB], but it was easy to use and it held the attention span of everyone.*"

During the system demonstration, students were engaged and attentive to the researchers. We designed a short story for students to fill in the blank spaces based on the correct answers found in the laboratory manual (see supplementary materials). As we navigated the characters around the classroom to interact with the various IoT devices, the researchers would input the correct answers via text in order to trigger the virtual-physical interactions. As stated in Section 4.2 , the students were able to easily follow along by viewing the phone screen being broadcast onto the classroom projector.

One interesting design that came from this study was the inclusion of **Laboratory Mode** on the IoT PCB (see Figure 10). Laboratory Mode is a feature that displays sensor data on the OLED screen of the IoT PCB from any of the various sensors in the Electronics Repository. This was particularly helpful during this study because it allowed the students to get the sensor data for their experiments; however, we found it to be quite useful in our later studies when users needed help testing sensors for programming with IoT Maker. For instance, when using the RGB sensor, you'll need to know the red, green, and blue values of the object(s) you're trying to identify with it before uploading the code to the IoT PCB. Using laboratory mode, users can easily collect those values and input them into IoT Maker to help make programming their IoT devices easier. See Section 5 for more information on this study.

4.6 Next Steps for ShARed IoT

As a result of our Projective Interview study and preliminary usability study, we found potential in our system's ability to create dynamic and engaging ShARed IoT experiences. These claims are substantiated by feedback from our experts who stated several interesting applications for the system. One such application was that of a golf course, which was originally a design suggestion by one of the researchers. For this application, students would be tasked with creating a moving obstacle for the course whose functions are triggered through interactions with AR characters. We decided to adopt this application for our User Study so we could see how a different set of users would respond to designing, building, and programming their own devices, then using ShARed IoT to interact with them. This study is explained in depth in the next section.

5 USER STUDY

As a means to gaining more insight into how people could use the ShARed IoT platform to create unique shared AR-IoT experiences, we conducted six two-hour workshops with several groups of undergraduate and graduate students at a large midwestern university (N = 13; ages 18-34). This study aimed to answer the following research questions:

RQ1: How do the participants utilize IoT Maker and IntARact to design their AR-IoT interactions?
RQ2: Which secondary devices are being used by participants to build they obstacle courses?
RQ3: How do shared AR-IoT interactions play a role in collaborative tasks outside of using the applications?

For this study, we collected mostly quantitative data and some qualitative data to assess our two research questions. We analyzed the devices and functions that users created, observational field notes taken by one of the researchers, as well as the pre- and post-study survey data.

5.1 Recruitment Method & Safety Precautions

Students were recruited via word of mouth, postings on our social media pages, as well as postings on University email lists. Informed consent regarding the study was received from all students. The participants were asked to sign up for time slots for the study and groups were made based on the number of students who signed up for a particular time slot. We limited the number of students to 3 per session in order to make space for adequate social distancing practices. University and laboratory Standard Operating Procedures were in place to ensure all students were safe and comfortable. Lastly, all equipment was sanitized at the beginning and at the end of each study using disinfectant wipes provided to us by the University.

Overall, we had 13 participants in total (8 male, 5 female) across six total workshops. Each student received $20 compensation in return for completing the study. See Table 1 for participant demographics.

Name	Sex	Age	Phys. Comp. Exp.						Electronics Exp.					Electro-Mech. Exp.						AR Exp.					
			Q1	Q2	Q3	Q4	Q5	Q6	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q6	Q1	Q2	Q3	Q4	Q5	Q6
May	F	27	6	6	6	5	5	5	6	6	6	6	6	5	4	4	3	4	3	6	6	6	4	3	4
Ken	M	18	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	4	6	6
Gary	M	18	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	2	6	3	2	2
Amanda	F	26	–	–	–	–	–	–	5	5	4	2	2	2	1	4	2	2	2	5	3	6	3	4	3
Louis	M	34	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	6	5	5	4
Miranda	F	21	3	3	5	3	3	3	5	5	2	3	4	–	–	–	–	–	–	5	5	6	1	1	2
Bill	M	18	5	6	4	3	3	2	5	5	3	3	2	5	5	4	2	2	1	5	6	4	4	4	3
Nate	M	18	3	3	4	3	3	3	4	4	3	3	3	4	4	4	2	2	2	4	4	6	3	3	3
Anna	F	28	7	7	6	5	6	5	7	7	7	7	7	7	7	7	7	7	7	7	6	6	5	5	5
Yunbo	M	18	5	5	4	2	2	2	6	5	4	5	4	–	–	–	–	–	–	5	5	6	4	3	4
Marshall	M	21	5	5	5	3	3	5	5	5	5	2	2	3	3	4	4	2	2	6	6	6	2	2	5
Shay	F	18	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	6	5	3	2	2
Ashton	M	25	–	–	–	–	–	–	6	6	4	4	2	2	–	–	–	–	–	6	5	7	3	3	4

Table 1. *Pre-Survey Results and demographic information from the User Study. All questions are based on a 7-point Likert Scale (1 - strongly disagree, 7 - strongly agree). Q1-6 can be found in Appendix A of this paper.*

5.2 Study Procedures

Upon arrival to the research area, participants were asked to fill up a pre-study survey with several demographic questions and questions regarding their expertise in 4 areas, (1) Physical Computing Devices, (2) Electronics and Circuits, (3) Electro-Mechanical Devices, and (4) Augmented Reality. We modeled the research area to resemble a maker space, giving students access to a workstation, fabrication materials, and tools. Following the same procedure as the Projective Interview, we adapted the questions from the internet self-efficacy scale given by Eastin, et. al [15]. Once the group was finished with the survey, they were taken through a tutorial of the IntARact app first, followed by the ShARed IoT app. Pre-made IoT devices were given to them to use during the tutorial. This was done to give them a good understanding of how the AR connects to the IoT devices and how to author interactions between the different content. We also wanted to give them an idea as to how the golfing would work, so we had them just do one round of golf with our devices before putting the phones down.

Once they had a satisfactory understanding of how the system worked, they were introduced to the IoT Maker application and explained the task of the user study. The task was to work together during a build session to design an IoT device that would serve as an obstacle for the mini golf course. Each device was required to utilize at least two of our secondary devices, but any of the devices could be chosen. Users were also given the choice of re-programming the devices that we designed by adding more functionality to them. For this task, users were given several prototyping materials to use for their devices including cardboard, paint, feathers, popsicle sticks, hot glue, tape, plastic straws, and more. Approximately 1 hour was allotted to having participants brainstorm, build, and program their obstacles.

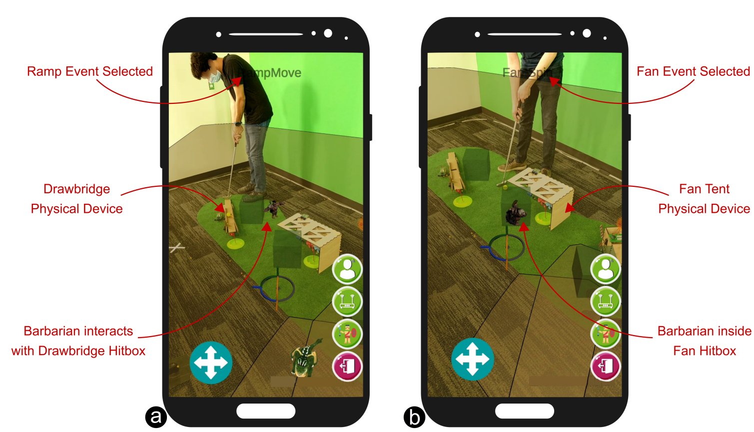

Figure 12: *A depiction of screenshots from our user study: (a) User prepares to use the Barbarian AR Character to activate the user-made drawbridge ramp device. (b) Participant attempts to putt the golf ball after the Barbarian is used to activate the pre-made fan device.*

After they had finished this part of the study, the code was uploaded to their IoT PCBs and the participants were asked to create the interactions using IntARact. Once the cloud anchor was placed by the host, all other participants and researchers joined the room and began golfing. At the conclusion of the study, participants were asked to fill out a post-study survey where they were asked questions regarding their experience using the system and other questions regarding system usability. The results from this survey will be given in the next section of this paper.

6 RESULTS

In this section, we will discuss the results from AR-IoT golfing User Study. We present (1) what the participants designed and programmed for their golf course obstacle, and (2) key takeaways and observations extracted from our post-study survey and field notes. Again, we report all Likert-scale questions with the mean (m), standard deviation (σ) and variance (V). All participant names are replaced by pseudonyms to protect participant identity.

6.1 Golf Course Obstacles

During the workshop, our participants were very creative when crafting their own obstacles for the mini golf course. Some of them used only the minimum of two secondary devices, whereas two groups used more than the minimum number to make their obstacle, and one group of three consisting of Louis, Amanda, and Miranda decided to each make one obstacle instead of collaborating. We found that the group that didn't collaborate took the longest time in the design stage due to their non-collaborative efforts; however, it resulted in a more broad set of devices that were made. Figure 13 shows the custom obstacles that our participants crafted.

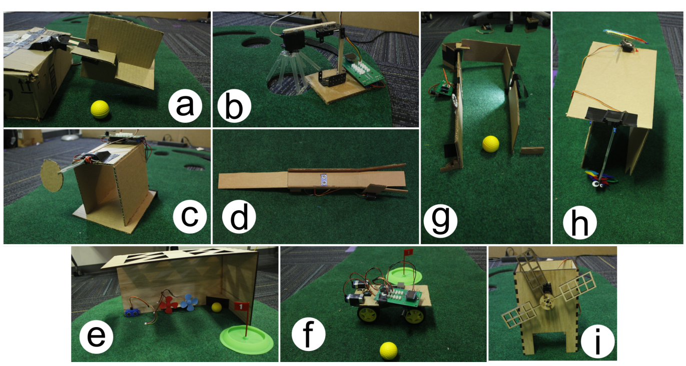

Figure 13: *The custom golf obstacles fabricated by our participants: (a) Golf Turnstile, (b) Octopus Spinner, (c) Pendulum, (d) Ramp, (e) Fan (pre-designed by researchers), (f) Crazy Car, (g) Gate, (h) Pendulum and Spider Release (on back), (i) Windmill (pre-designed by researchers).*

Among the 8 obstacles that were crafted, the Ultrasonic Sensor and the Light Sensor were the only two sensors that were used. We believe this to be due to the fact that the Ultrasonic sensor can easily detect motion from a reasonable distance, while the light sensors can detect changes in light levels if something blocks the light source from the sensor (i.e. the golf ball). Since the other sensors weren't adept at this type of motion detection, they were less favorable by participants.

Additionally, we noticed that the most commonly used actuators were the big 180° and continuous rotation servo motors as 6 of the devices used them in their designs. Lastly, the LEDs were also commonly integrated into their obstacles, by turning on light patterns and displaying faces when certain interactions were triggered. There was one device that was designed to only include the Neopixel Ring 12 and the Piezo Sound Buzzer to create a distraction for the golfers.

Surprisingly, none of the groups took the opportunity to re-program our existing windmill and fan despite their designs being finalized. Nonetheless, every group still decided to use at least the windmill during the final golf activity, while the fan was not so popular among the groups.

6.2 Participant Engagement and Enjoyment

We found our participants were engaged throughout the study, especially during our build session. In our observational field notes, we noted that several participants really enjoyed the idea of creating AR-IoT interactions. May mentioned to us that she was a part of a young golfer's club as a child and really liked that, *"you guys are incorporating something like AR into a favorite hobby of mine."* Ken and Gary showed us how much they enjoyed using the system by taking several turns blocking each others golf swings with their custom "Octopus Spin" device and our pre-designed windmill. Finally, Bill and Nate showed their enthusiasm during the study, but were the only ones who sent a follow up email to us asking to participate in any future studies that we may have.

It is worth noting that there were some differences between the effort that was exhibited by the older participants. We noticed that most of the 18 year old participants were more adventurous with their ideas and really wanted to put their all into, whereas the older participants (age > 21) were less likely to utilize their creativity. For example, Ken and Gary spent some time giving a backstory to the "Octopus Spin" device and explained how they were trying to mimic as closely as possible the image that they had seen on the internet. Also, Yunbo and Marshall made a very interesting "Car Blocker" obstacle whose sole purpose was to move quickly back and forth in front of the golf hole. May, on the other hand, wasn't very interested in using any of the materials that we had provided to her and just wanted to focus on programming her "Distraction" device, and Amanda just wanted to make a simple pendulum by having the servo motor move a piece of cardboard to-and-fro. Nonetheless, each of our participants were engaged with each other and the researchers throughout.

6.3 Overall Responses from Participants

Overall, our participants found the system to be usable by them and the different parts of the system to be well integrated. In the post-study survey, we queried the participants about the IoT PCB, IoT Maker, IntARact, and ShARed IoT individually, and finished with questions from the System Usability Scale (SUS) [5, 45]. A graphical representation of these questions can be seen in Figure 15 and the SUS scores are presented by participant in Figure 14.

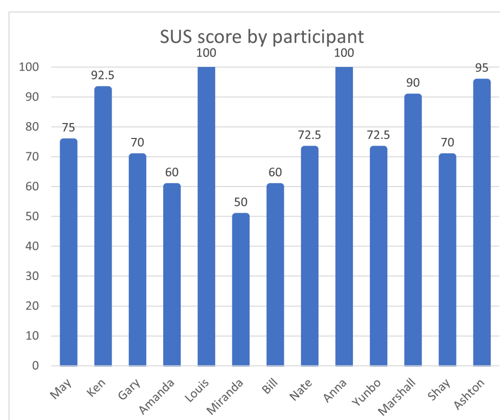

Figure 14: *System Usability Scale (SUS) scores by participant. The scores were calculated using traditional calculation methods as laid out by several prior works [5, 45].*

6.3.1 IoT PCB Impressions: Users generally enjoyed using the IoT PCB because of its simplicity and plug-and-play design. When asked if it was easy to connect the motors/sensors to it, all participants responded favorably (m = 6.46, σ = 0.63, V = 0.4) and said that the easily connecting electronics helped bring their physical structures to life (m = 6.46, σ = 0.63, V = 0.4). Users reported that it didn't require a lot of training to use the device (m = 6.54, σ = 0.5, V = 0.25), while some users preferred to use more knowledge about electronics to operate them than others (m = 6.54, σ = 0.84, V = 0.71). Overall, our IoT PCB did a good job at helping simplify the electronics for our participants.

6.3.2 IoT Maker Impressions: Our participants also enjoyed using the IoT Maker application, stating that it was usable by them (m = 6.69, σ = 0.46, V = 0.21) and that the blocks made programming the devices easy (m = 6.69, σ = 0.61, V = 0.37). However, some users did indicate that they were indifferent about whether the system was attractive to them (m = 6.46, σ = 0.93, V = 0.86) and whether the live simulator actually helped them visualize what would happen to the devices (m = 6.54, σ = 0.93, V = 0.86). We attribute this to the fact that it was hard for some users to actually visualize which angle position was "0°" on the 180° servo motors (completely clockwise or completely counter-clockwise). To address this, we plan to implement a simple debugging workflow

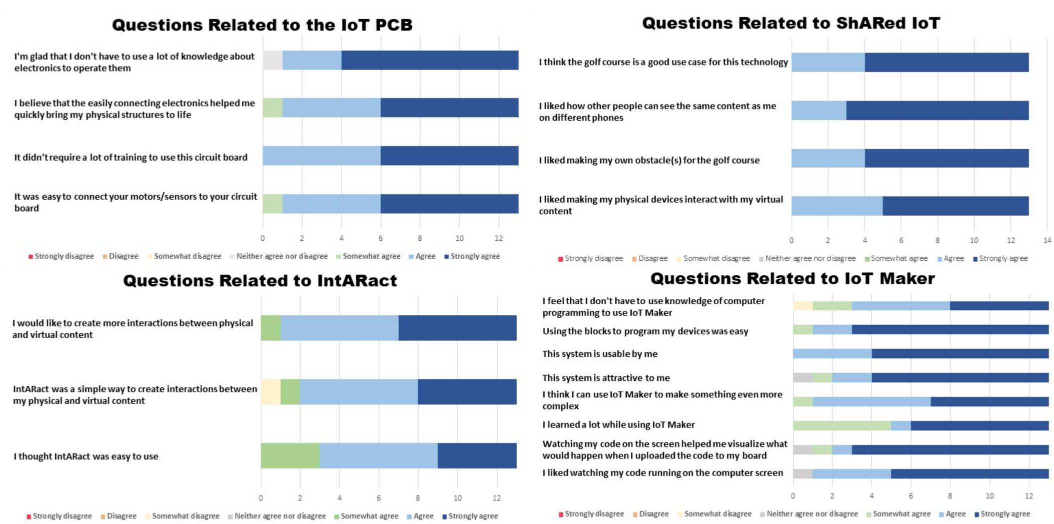

Figure 15: *A graphical representation of our post-study survey results. The questions were broken up into 4 sections relating to the IoT PCB, IoT Maker, IntARact, and ShARed IoT.*

to accompany the IoT Maker application. Finally, our users generally believed that IoT Maker could be used to make something even more complex (m = 6.38, σ = 0.62, V = 0.39).

6.3.3 IntARact Impressions: Our IntARact app was the least favorable part of the system according to the users. Curiously, participants thought that IntARact was somewhat easy to use (m = 6.08, σ = 0.73, V = 0.53), but they did **not** think that IntARact was a simple way to create interactions between physical and virtual content (m = 6.08, σ = 1.07, V = 0.15). We found that the app was a bit confusing because it is a flat 2D interface that is used to author 3D interactions. The other issue was that IntARact is a separate application from ShARed IoT and requires a lot of forethought from the users and explanations from the researchers. Rather, we believe that the application should be more in-situ by allowing users to dynamically create AR content and design the interactions between them and the IoT devices. This observation is consistent with comments from the participants who stated that *"... the subject and the target was not very clear how it works,"* and *"... the interface (visuals/ color scheme) is very simple and user friendly, but it does require a walk through for setup of functionality (i.e., cannot be done without guidance/setup not intuitive),"* when asked what they would improve about IntARact. These concerns are addressed in the Limitations & Future Work section of this paper.

6.3.4 ShARed IoT Impressions: ShARed IoT was the crux of the system and allowed for shared AR-IoT experiences between multiple users. Our participants found the mini golf course to be a good use case for this system (m = 6.69, σ = 0.46, V = 0.21) and that they enjoyed making their own obstacles for the golf course (m = 6.69, σ = 0.46, V = 0.21). All the participants enjoyed creating their own AR-IoT interactions (m = 6.62, σ = 0.49, V = 0.24). When asked about their shared experiences, all the participants liked that other people can see the same content as them on different phones (m = 6.77, σ = 0.42, V = 0.18). We found that the system integrated the AR content and IoT devices well across the multiple devices. The results show that our system is effective at allowing users with and without experience in our four areas of concentration to design and author interactions between AR and IoT content. What is more, when asked to rate the system overall, the participants gave us a total SUS score of 77.5, which exceeds the generally accepted benchmark of 68. Future versions of the ShARed IoT system will aim to improve our usability scores.

6.4 Summary

Overall, our participants enjoyed using the ShARed IoT system. We found that the IoT PCB was helpful in lowering the barrier of entry for all participants to create an electro-mechanical device. Further, the IoT Maker system excelled at helping users easily and quickly program those devices with its block-programming interface and live simulation tool. The IntARact app overall needs improvement to help users design the interactions between the physical and virtual content. Finally, the ShARed IoT platform integrated the different areas very well to help our users create their own AR-IoT interactions. It also provided a good platform to allow for a unique golfing exercise. The participants gave us a strong total SUS score of 77.5, which shows that the system can be used to design and program IoT devices to be used and controlled among multiple users for shared AR-IoT experiences.

7 DISCUSSION

The results from our User Study show that the ShARed IoT system is capable of giving both novice and expect users the ability to design their own interactions between AR content and IoT devices. Systems such as ShARed IoT, lowers the **barrier** to enter this type of work, while concurrently shifting the **point** of entry higher (i.e. enabling users to do more at the beginning with limited knowledge). In the following section, we discuss our findings across our three studies.

7.1 Insights Collected from All Three Studies

The use of our system requires the user to perform multiple different design tasks through programming, device creation and interaction design. This, along with the open-ended nature of our system, can place pressure on a user in terms of creativity. An expert interviewed as part of our study mentioned that giving users a tool to guide their design process and help them throughout the exercise of designing and creating their IoT device would greatly enhance their experience. To this end, we included the live simulator portion of our IoT Maker application, which was intended to help users design their devices with greater ease. As noted in the results, we found that users struggled with understanding some of the less explicit instructions provided to them by the live simulator. This is an interesting conundrum that many makers encounter when designing with devices that use Pulse Width Modulation (PWM) signals and similar techniques for device control. We find this to be a necessary step to really learning about the secondary devices because it forces the user to create iterations. This can be good for users interested in really learning more about how physical computing devices work.

Our preliminary usability study outlined in Preliminary Usability Study with Middle School Students helped test and observe user's thoughts and reactions whilst using the IoT PCB and electronics repository in a learning setting. However, due to classroom policies regarding the use of cellphones, the AR component of the toolkit was presented to the class by a researcher, rather than allowing the children to use it themselves. Based on the feedback received from the study and the enthusiasm students showed towards the AR component of the toolkit, we conducted the study outside of the classroom environment so that users can experience the entirety of ShARed IoT, rather than just the IoT PCB. Although we could have chosen to target the previous demographic with Middle School students, we chose a different demographic because we wanted to test usability and the quality of our system with users of variable experience using Physical Computing Devices, Electronics, Electro-Mechanical Devices, and AR. Given that younger audiences would be less likely to possess these same qualities, we found it more beneficial to target University-level participants for our final user study.

7.2 Areas of Improvement

During our final study, participants crafted a total of 7 golf course obstacles, and one obstacle that only had secondary devices plugged into the IoT PCB, but no external materials attached to them. The features that the participants seemed to enjoy the most were the AR-IoT interactions made with ShARed IoT and IoT Maker. On the other hand, there was a lot of frustration when users would perform an action incorrectly or when their devices didn't function the way they had intended it to. There were a few times where users were disappointed that something didn't work and we would spend time debugging and helping them fix the issues. Also, we experienced WiFi connectivity issues during some of the studies, which caused a lag between the phone and the IoT devices. Greater care will need to be taken in the future to ensure these issues do not persist. Lastly, the design of the IoT PCB played a role in some of the frustrations. Since all of the soldered connections are exposed, several of our IoT PCB pins would become unsoldered, which made debugging difficult at times. This was also an issue during the Middle School study when a student spilled one of the chemicals onto the top of the PCB, corroding the power switch. Future iterations of this system will ensure a protective sleeve is designed to be placed around the PCB to protect the connections to the actual PCB, while still maintaining easy access to all pins and switched located on the PCB.

Each of these issues were reflected in some of the post-study survey results, including some of the lower SUS scores that we received from several participants. However, despite these challenges, our system was heralded as usable given the 77.5 overall SUS score (where the minimum score for usability is 68), and easy to use as indicated by the post-study survey results. All-in-all, we believe the results from our studies provide enough evidence to substantiate the claims of the contributions. However, no work is exempt from critique and limitation; thus, we discuss the limitations of our system and some future considerations for research directions in the next sections of this paper.

7.3 Implications for Future AR-IoT Systems

The role of AR in systems similar to ShARed IoT can become a powerful tool for enabling shared experiences between multiple users. We've explored an avenue that allows virtual content to affect what happens in a physical space. Today, there are many occupations that turned to AR for employee training and, in the future, the virtual and physical realms will become more and more seamlessly integrated with one another [1, 16]. ShARed IoT fits in this future because, as researchers continue to push the boundaries of AR, the ability to cause physical changes to an environment through interactions with virtual objects leverages what is powerful about both AR and IoT devices. Another note is that our users were enthusiastic about how the system could be used in future contexts. We asked our users to describe use-cases that they could think of that could use ShARed IoT, and among the many answers we received, one user noted that, *This could be very suitable for a social distancing design concept where you can see in AR what someone is doing in real-time and share ideas and simulations.* Given that the COVID-19 pandemic has ushered in a new wave of health and safety protocols, it is imperative that researchers continue to study how AR can be used to enable these practices safely (especially in co-located spaces, which is the case with ShARed IoT).

8 LIMITATIONS & FUTURE WORK

Exploring the ShARed IoT system allowed us to create new example use-cases for this technology, while simultaneously providing insights for more work to be done in other embodiments. As presented in Section 7.2, the system does suffer from minor stability issues, in part due to lack of optimization with weaker connections, quality control with board assembly, and long setup processes. In this section, we will outline the further improvements based on expert and user feedback as well as future steps.

8.1 Divided Workflow

An aspect of our system that the users found to be limiting was having the workflow divided across three separate applications. As mentioned in Section 6.3.3, the disconnect and task switching between the three applications to develop a single use case, was challenging for some users. One expert pointed out that for the process to feel natural, users need to create a link between how their physical devices connect to the AR content. The cognitive cost to switch between programs can interrupt the creative process and feel unnatural [52]. We plan to address this by building event creation into our AR app, in situ in order to introduce a feeling of spontaneity and reduce the added cognitive load in switching and learning multiple interfaces. Our vision is to allow users to select how they want to interact with their AR or physical content in real time, which in-turn will yield more time for user immersion in their desired vision (a benefit noted in the Software Implementation section of this paper).

8.2 Multi Modal Deployment

ShARed IoT runs primarily on a smart phone. The system runs on an Android phone using Google's ARCore package. However, we recognize that being required to hold a phone can limit the experience by nature of having to move a camera around and using a small screen with limited modality. We believe utilizing a Head-Mounted Display (HMD) such as the Microsoft Hololens 2 to create a hands-free experience will provide an extra layer of immersion for users [50]. We believe greater immersion can lead to greater creativity, learning, and engagement, leading to the development of more complex experiences. But these interaction modalities made specifically for a unique system such as ShARed IoT require additional studies and evaluations, which is part of our future work.

8.3 Co-location Collaboration

ShARed IoT was designed for a collaborative virtual-physical interaction. The requirement of the physical devices currently constrains the users to be present in a co-located space. As previously, mentioned in Collaborative Technologies and Shared Augmented Reality Experiences sections, social presence increases engagement with the provided material; however, our current workflow presents an accessibility challenge. In the case that collaborators are unable to access the shared working space, a partly remote working space can be explored for part of the user group to participate. We plan to expand the system to allow for such remote participation in shared experiences in the future. This can work in conjunction with the previously mentioned HMDs since these changes will flatten our system's accessibility curve by allowing people to connect from wherever they want and with any display or device they have available to them.

8.4 Component Variance

A surprising observation was made from our post survey questionnaire "If I could make my own use-case for this technology (similar to the golf course), I would make...". Four of our users remarked how they would use this system to implement some kind of racetrack with IoT cars. Similar to the work recently produced by Nintendo [55], an AR kart racing game with virtual obstacles could be designed. Modifying our system to enable the production of complex devices, such as small IoTed cars, presents a strong use case for showing how users can weave physical content with AR spaces. This leads us to realizing the importance of allowing modification and programming custom electronics into our ecosystem as users can customize their content as desired.

As noted in Section 3.1, our system is currently optimized to work with the electronics highlighted in our repository (See Figure 3). While this may be a benefit to novice users who are only starting to figure out how IoT programming works, this can be seen as a creative restriction for people fluent in electronics programming or interested in learning beyond the basics. Our goal is to provide a framework for users to be able to program their own electronics with IoT Maker to provide a personalized experience. This would enable a broader user group to enjoy the experience, as they would be able to add their custom components to the existing repository. Effectively, this would increase the longevity of the system by allowing it to adapt to new advances in technology and enable larger variations and creativity.

8.5 Enhancements in Design and Prototyping

Researchers have developed Computer Aided Design applications that provide similar functionality [61]. Based on this, a 3D prototyping tool that provides users with design suggestions for IoT devices they want to fabricate could be a beneficial enhancement to our system. This proposed 3D-Modelling software can contain a repository of community and previously made designs, which can encourage either reuse of or changes to prior designs by drawing inspiration from it to make their own. Moreover, the tool could also help the user by providing 3D models of secondary devices in the electronics repository, whilst providing connectors such as in Shape Structuralizer [10] that could serve as an alternative to using glue and tape for construction of their IoT device.

8.6 Static IoT Hitboxes

One limiting factor of the way our AR-IoT interactions are set up, is the way a character is able to detect collision with an IoT device. As pointed out in Figure 5, the link between AR-IoT interactions is a green box collider (hitbox), placed in AR space where the device sits in the real world. This causes problems if the IoT device is mobile (such as a car), since the hitbox is not currently set up to move with the device, meaning, it will always stay in the same spot virtually. This is an immersion-breaking limitation that we are looking to address in the next iteration of this system. This kind of problem has been addressed in the recent Mario Kart AR game, where physical devices display specific images (like a coin or banana) that an AR camera scans in order to map its virtual location dynamically [55].

8.7 Security Risks

The current design of the system tailors better towards controlled environments with secured WiFi networks. When running the system as intended, all connected PCBs show their Local Area Network (LAN) IP addresses so the system knows which device contains what functions. Alongside this, all connected phones are subject to the Google and Photon privacy policies when using the network capabilities of Augmented Reality, Cloud Anchors, and multiplayer connections respectively [26, 27, 60]. Users are subject to malicious attacks from lower-scale hackers on their WiFi network to large-scale hackers trying to peek into user data stored on the servers of the aforementioned services. This would however be an interesting research topic to explore teaching users the risks of using AR technology in how it can potentially expose identifying data. A workshop may look like showing users the type of information stored during an AR session, and having a different user 'hack' into the network and start affecting the PCBs and/or the AR experience.

9 CONCLUSION

ShARed IoT, is an AR-IoT system specifically designed for shared experiences in AR and with IoT devices across multiple smart phones. The design of this system was motivated by the need to make (a) shared AR content interactive with physical devices, and (b) technologies that make augmented collaborative tasks easier and more engaging. Our system encourages users to design, build, and program physical IoT devices and author AR content for a shared AR experience. We conducted a Projective Interview study with 9 UX experts, followed by an initial study with Middle School students, and finally a field study with 13 participants. We also provide conclusions drawn from the results of these studies, as well as more work to be done for future iterations of the project.

REFERENCES

[1] Günter Alce, Karl-Johan Klang, Daniel Andersson, Stefan Nyström, Mattias Wallergård, and Diederick Niehorster. 2020. *Using Augmented Reality to Train Flow Patterns for Pilot Students - An Explorative Study.* Springer, Italy, 215–231. https://doi.org/10.1007/978-3-030-58465-8_17

[2] Hayward P. Andres. 2012. Technology-Mediated Collaboration, Shared Mental Model and Task Performance. *Journal of Organizational and End User Computing* 24, 1 (2012), 64–81. https://doi.org/10.4018/joeuc.2012010104

[3] Autodesk Autodesk. 2020. Cloud Powered 3D CAD/CAM Software for Product Design: Fusion 360. https://www.autodesk.com/products/fusion-360/overview

[4] Ronald T. Azuma. 1997. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments* 6, 4 (Aug. 1997), 355–385. https://doi.org/10.1162/pres.1997.6.4.355

[5] Aaron Bangor, Philip T Kortum, and James T Miller. 2008. An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction* 24, 6 (2008), 574–594.

[6] British Broadcasting Corporation (BBC). 2020. Micro:bit. https://microbit.org/.

[7] Andrea Beetz, Kerstin Uvnäs-Moberg, Henri Julius, and Kurt Kotrschal. 2012. Psychosocial and Psychophysiological Effects of Human-Animal Interactions: The Possible Role of Oxytocin. *Frontiers in Psychology* 3 (2012), 15. https://doi.org/10.3389/fpsyg.2012.00234

[8] Cynthia L Breazeal. 2000. *Sociable Machines: Expressive Social Exchange Between Humans and Robots.* Ph.D. Dissertation. Massachusetts Institute of Technology.

[9] Yvonne M. Caldera, Aletha C. Huston, and Marion O'Brien. 1989. Social Interactions and Play Patterns of Parents and Toddlers with Feminine, Masculine, and Neutral Toys. *Child Development* 60, 1 (Feb. 1989), 70. https://doi.org/10.2307/1131072

[10] Subramanian Chidambaram, Yunbo Zhang, Venkatraghavan Sundararajan, Niklas Elmqvist, and Karthik Ramani. 2019. Shape Structuralizer: Design, Fabrication, and User-driven Iterative Refinement of 3D Mesh Models. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. ACM Press, Glasgow, Scotland Uk, 1–12. https://doi.org/10.1145/3290605.3300893

[11] Bruce Christie. 1985. *Human Factors of Information Technology in the Office.* John Wiley & Sons, Inc., USA.

[12] Stanley Coren and Joan S Girgus. 1980. Principles of perceptual organization and spatial distortion: the gestalt illusions. *Journal of Experimental Psychology: Human Perception and Performance* 6, 3 (1980), 404.

[13] Dragoş Datcu, Stephan G. Lukosch, and Heide K. Lukosch. 2016. Handheld Augmented Reality for Distributed Collaborative Crime Scene Investigation. In *Proceedings of the 19th International Conference on Supporting Group Work* (Sanibel Island, Florida, USA) *(GROUP '16)*. Association for Computing Machinery, New York, NY, USA, 267–276. https://doi.org/10.1145/2957276.2957302

[14] Volodymyr Dziubak, Ben Lafreniere, Tovi Grossman, Andrea Bunt, and George Fitzmaurice. 2018. Maestro: Designing a System for Real-Time Orchestration of 3D Modeling Workshops. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 287–298. https://doi.org/10.1145/3242587.3242606

[15] Matthew S Eastin and Robert LaRose. 2000. Internet self-efficacy and the psychology of the digital divide. *Journal of computer-mediated communication* 6, 1 (2000), JCMC611.

[16] Martin Eckert, Julia Volmerg, and Christoph Friedrich. 2018. Augmented Reality in Medicine: Systematic and Bibliographic Review. *JMIR Mhealth Uhealth* 7 (05 2018), e10967. https://doi.org/10.2196/10967

[17] Espressif. 2020. ESP32 Overview | Espressif Systems. https://www.espressif.com/en/products/socs/esp32/overview

[18] Espressif. 2020. ESP8266 Overview | Espressif Systems. https://www.espressif.com/en/products/socs/esp8266/overview

[19] Jerry Alan Fails, Allison Druin, and Mona Leigh Guha. 2010. Mobile Collaboration: Collaboratively Reading and Creating Children's Stories on Mobile Devices. In *Proceedings of the 9th International Conference on Interaction Design and Children* (Barcelona, Spain) *(IDC '10)*. Association for Computing Machinery, New York, NY, USA, 20–29. https://doi.org/10.1145/1810543.1810547

[20] A. Fathi, J. K. Hodgins, and J. M. Rehg. 2012. Social interactions: A first-person perspective. In *2012 IEEE Conference on Computer Vision and Pattern Recognition*. IEEE, Providence, RI, 1226–1233. https://doi.org/10.1109/CVPR.2012.6247805

[21] Gene D. Fowler and Marilyn E. Wackerbarth. 1980. Audio teleconferencing versus face-to-face conferencing: A synthesis of the literature. *Western Journal of Speech Communication* 44, 3 (1980), 236–252. https://doi.org/10.1080/10570318009374009 arXiv:https://doi.org/10.1080/10570318009374009

[22] Github Github. 2020. Build software better, together. https://github.com/

[23] Terrell Glenn, Ananya Ipsita, Caleb Carithers, Kylie Peppler, and Karthik Ramani. 2020. StoryMakAR: Bringing Stories to Life With An Augmented Reality & Physical Prototyping Toolkit for Youth. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376790

[24] Pokemon GO. 2019. Pokémon GO - Official Shared AR Experience Tutorial Trailer |. https://www.youtube.com/watch?v=PMTC7vbdA9Y
[25] Google. 2020. Cloud Firestore. https://firebase.google.com/docs/firestore
[26] Google. 2020. How visual data powers shared AR experiences | Google Developers. https://developers.google.com/ar/cloud-anchors-privacy.
[27] Google. 2020. Privacy Policy – Privacy & Terms. https://policies.google.com/privacy.
[28] Google. 2020. Share AR experiences with Cloud Anchors | ARCore | Google Developers. https://developers.google.com/ar/develop/unity-arf/cloud-anchors/overview
[29] Google Google. 2020. Googel-Docs. https://www.google.com/docs/about/
[30] The LEGO Group. 2019. LEGO Mindstorms. https://www.lego.com/en-us/mindstorms.
[31] Khaled Hassanein and Milena M. 2013. Manipulating social presence through the web interface and its impact on consumer attitude towards online shopping. http://hdl.handle.net/11375/5331
[32] Anders Henrysson, Mark Billinghurst, and Mark Ollila. 2005. Face to face collaborative AR on mobile phones. In *Proceedings - Fourth IEEE and ACM International Symposium on Symposium on Mixed and Augmented Reality, ISMAR 2005*, Vol. 2005. IEEE, Vienna, Austria, Austria. https://doi.org/10.1109/ISMAR.2005.32
[33] Juan Pablo Hourcade, Benjamin B. Bederson, Allison Druin, and Gustav Taxén. 2002. KidPad: Collaborative Storytelling for Children. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems* (Minneapolis, Minnesota, USA) *(CHI EA '02)*. Association for Computing Machinery, New York, NY, USA, 500–501. https://doi.org/10.1145/506443.506449
[34] Ke Huo, Yuanzhi Cao, Sang Ho Yoon, Zhuangying Xu, Guiming Chen, and Karthik Ramani. 2018. Scenariot: Spatially Mapping Smart Things Within Augmented Reality Scenes. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173793
[35] Ke Huo, Tianyi Wang, Luis Paredes, Ana M. Villanueva, Yuanzhi Cao, and Karthik Ramani. 2018. SynchronizAR: Instant Synchronization for Spontaneous and Spatial Collaborations in Augmented Reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 19–30. https://doi.org/10.1145/3242587.3242595
[36] Google Inc. 2020. Google's 3D animals. https://www.google.com/
[37] Niantic Inc. and The Pokemon Company. 2020. Catch Pokémon in the Real World with Pokémon GO! https://www.pokemongo.com/en-us/
[38] Adafruit Industries. 2020. Adafruit Circuit Playground. https://www.adafruit.com/index.php?main_page=category&cPath=888.
[39] Adafruit Industries. 2020. Adafruit HUZZAH32 - ESP32 Feather Board | Adafruit Industries. https://www.adafruit.com/product/3591
[40] Inc. Innovation First International. 2021. Welcome to VEX Robotics. https://www.vexrobotics.com/
[41] Spatial io. 2020. Spatial. https://spatial.io/
[42] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. Association for Computing Machinery, New York, NY, USA, 234–241.
[43] K. Kim, M. Billinghurst, G. Bruder, H. B. Duh, and G. F. Welch. 2018. Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008–2017). *IEEE Transactions on Visualization and Computer Graphics* 24, 11 (2018), 2947–2962.
[44] Germán Leiva, Cuong Nguyen, Rubaiat Habib Kazi, and Paul Asente. 2020. Pronto: Rapid Augmented Reality Video Prototyping Using Sketches and Enaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376160
[45] James R Lewis. 2018. The system usability scale: past, present, and future. *International Journal of Human–Computer Interaction* 34, 7 (2018), 577–590.
[46] Chuan-en Lin, Ta Ying Cheng, and Xiaojuan Ma. 2020. ARchitect: Building Interactive Virtual Experiences from Physical Affordances by Bringing Human-in-the-Loop. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376614
[47] Google LLC. 2019. Blockly. https://developers.google.com/blockly/
[48] Sean McDirmid. 2013. Usable Live Programming. In *Proceedings of the 2013 ACM International Symposium on New Ideas, New Paradigms, and Reflections on Programming & Software* (Indianapolis, Indiana, USA) *(Onward! 2013)*. Association for Computing Machinery, New York, NY, USA, 53–62. https://doi.org/10.1145/2509578.2509585
[49] Sharan B Merriam and Elizabeth J Tisdell. 2015. *Qualitative research: A guide to design and implementation.* John Wiley & Sons, San Francisco, CA, USA.

[50] Microsoft. 2019. Microsoft HoloLens: Mixed Reality Technology for Business. https://www.microsoft.com/en-us/hololens/

[51] S. N. H. Mohamad, A. Patel, R. Latih, Q. Qassim, Liu Na, and Y. Tew. 2011. Block-based programming approach: challenges and benefits. In *Proceedings of the 2011 International Conference on Electrical Engineering and Informatics*. IEEE, Bandung, Indonesia, 1–5.

[52] Stephen Monsell. 2003. Task switching. *Trends in cognitive sciences* 7, 3 (2003), 134–140.

[53] Koya Narumi, Steve Hodges, and Yoshihiro Kawahara. 2015. ConductAR: an augmented reality based tool for iterative design of conductive ink circuits. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '15*. ACM Press, Osaka, Japan, 791–800. https://doi.org/10.1145/2750858.2804267

[54] Michael Nebeling, Janet Nebeling, Ao Yu, and Rob Rumble. 2018. ProtoAR: Rapid Physical-Digital Prototyping of Mobile Augmented Reality Applications. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–12. https://doi.org/10.1145/3173574.3173927

[55] Nintendo. 2020. Mario Kart Live: Home Circuit – Official Site. https://mklive.nintendo.com/

[56] Octi. 2020. Octi - The first people-powered social AR platform. https://www.octi.tv/

[57] K. Ozacar, T. Hagiwara, J. Huang, K. Takashima, and Y. Kitamura. 2015. Coupled-clay: Physical-virtual 3D collaborative interaction environment. In *2015 IEEE Virtual Reality (VR)*. IEEE, Arles, France, 255–256.

[58] E. Pasternak, R. Fenichel, and A. N. Marshall. 2017. Tips for creating a block language with blockly. In *2017 IEEE Blocks and Beyond Workshop (B B)*. IEEE, Raleigh, NC, USA, 21–24.

[59] Kylie Peppler and Sophia Bender. 2013. Maker Movement Spreads Innovation One Project at a Time. *Phi Delta Kappan* 95, 3 (Nov. 2013), 22–27. https://doi.org/10.1177/003172171309500306

[60] Photon. 2020. PUN. https://www.photonengine.com/pun

[61] Cecil Piya, Vinayak , Senthil Chandrasegaran, Niklas Elmqvist, and Karthik Ramani. 2017. Co-3Deator: A Team-First Collaborative 3D Design Ideation Tool. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 6581–6592. https://doi.org/10.1145/3025453.3025825

[62] Lev Poretski, Joel Lanir, and Ofer Arazy. 2018. Normative Tensions in Shared Augmented Reality. *Proceedings of the ACM on Human-Computer Interaction* 2, CSCW (Nov. 2018), 1–22. https://doi.org/10.1145/3274411

[63] PTC PTC. 2020. Communicate. Collaborate. Get it done. https://chalk.vuforia.com/

[64] Jan Recker, Jan Mendling, and Christopher Hahn. 2013. How collaborative technology supports cognitive processes in collaborative process modeling: A capabilities-gains-outcome model. *Information Systems* 38, 8 (2013), 1031 – 1045. https://doi.org/10.1016/j.is.2013.04.001

[65] Jun Rekimoto. 1996. TRANSVISION: A HAND-HELD AUGMENTED REALITY SYSTEM FOR COLLABORATIVE DESIGN. *Proceeding of Virtual Systems and Multimedia* 96 (1996), 6.

[66] John Rieman, Marita Franzke, and David Redmiles. 1995. Usability evaluation with the cognitive walkthrough. In *Conference companion on Human factors in computing systems - CHI '95*. ACM Press, Denver, Colorado, United States, 387–388. https://doi.org/10.1145/223355.223735

[67] Damien Constantine Rompapas, Christian Sandor, Alexander Plopski, Daniel Saakes, Joongi Shin, Takafumi Taketomi, and Hirokazu Kato. 2019. Towards large scale high fidelity collaborative augmented reality. *Computers & Graphics* 84 (2019), 24 – 41. https://doi.org/10.1016/j.cag.2019.08.007

[68] Ben Shneiderman, Catherine Plaisant, Maxine Cohen, Steven Jacobs, Niklas Elmqvist, and Nicholas Diakopoulos. 2016. *Designing the User Interface: Strategies for Effective Human-Computer Interaction* (6th ed.). Pearson, New York City, NY, USA.

[69] John Short, Ederyn Williams, and Bruce Christie. 1976. *The social psychology of telecommunications*. John Wiley, London, NY.

[70] SketchAR. 2020. https://sketchar.tech/

[71] Snaappy. 2020. Snaappy - Augmented Reality social network. https://snaappy.com/en/ Library Catalog: snaappy.com.

[72] Inc. Snapchat. 2020. The fastest way to share a moment! https://www.snapchat.com/

[73] Rick Spencer. 2000. The streamlined cognitive walkthrough method, working around social constraints encountered in a software development company. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '00*. ACM Press, The Hague, The Netherlands, 353–359. https://doi.org/10.1145/332040.332456

[74] Arduino Team. 2020. Get ready to Explore IoT with Arduino Education. https://blog.arduino.cc/2020/09/15/get-ready-to-explore-iot-with-arduino-education/

[75] Bird Brain Technologies. 2020. Bird brain Technologies: Hummingbird Robotics Kit. https://www.birdbraintechnologies.com/hummingbirdbit/.

[76] Balasaravanan Thoravi Kumaravel, Fraser Anderson, George Fitzmaurice, Bjoern Hartmann, and Tovi Grossman. 2019. Loki: Facilitating Remote Instruction of Physical Tasks Using Bi-Directional Mixed-Reality Telepresence. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*.

Association for Computing Machinery, New York, NY, USA, 161–174. https://doi.org/10.1145/3332165.3347872
[77] Unity. 2020. Unity's AR Foundation Framework. https://unity.com/unity/features/arfoundation
[78] Ana Villanueva, Zhengzhe Zhu, Ziyi Liu, Kylie Peppler, Thomas Redick, and Karthik Ramani. 2020. Meta-AR-App: An Authoring Platform for Collaborative Augmented Reality in STEM Classrooms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, Honolulu, HI, USA, 1–14.
[79] Ana Villanueva, Zhengzhe Zhu, Ziyi Liu, Kylie Peppler, Thomas Redick, and Karthik Ramani. 2020. Meta-AR-App: An Authoring Platform for Collaborative Augmented Reality in STEM Classrooms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376146
[80] Nicolas Villar, Daniel Cletheroe, Greg Saul, Christian Holz, Tim Regan, Oscar Salandin, Misha Sra, Hui-Shyong Yeo, William Field, and Haiyan Zhang. 2018. Project Zanzibar: A Portable and Flexible Tangible Interaction Platform. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174089
[81] Nicolas Villar, Haiyan Zhang, Daniel Cletheroe, Greg Saul, Christian Holz, Tim Regan, Oscar Salandin, Misha Sra, Hui-Shyong Yeo, and William Field. 2018. Project Zanzibar: A Portable and Flexible Tangible Interaction Platform. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–13. https://doi.org/10.1145/3173574.3174089
[82] WallaMe. 2020. WallaMe Augmented Reality | Hide messages in the real world. http://walla.me/
[83] Thomas Wells and Steven Houben. 2020. CollabAR: Investigating the Mediating Role of Mobile AR Interfaces on Co-Located Group Collaboration. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376541
[84] Karl D.D. Willis, Ivan Poupyrev, and Takaaki Shiratori. 2011. Motionbeam: a metaphor for character interaction with handheld projectors. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. ACM Press, Vancouver, BC, Canada, 1031. https://doi.org/10.1145/1978942.1979096
[85] Karl D. D. Willis, Takaaki Shiratori, and Moshe Mahler. 2013. HideOut: mobile projector interaction with tangible objects and surfaces. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction - TEI '13*. ACM Press, Barcelona, Spain, 331. https://doi.org/10.1145/2460625.2460682

A PROFICIENCY SCALES FOR EXPERTS

During our Projective Interview study, we adapted the Internet Proficiency Scale developed by Eastin and LaRose [15]. Changes were made to be relevant to the field in which the Expert stated they were proficient, but not to change the meaning of the statement. An example of our adaptation is below, and the rest of the proficiency scales were modified in a similar manner. Each question was evaluated on a 7-point Likert Scale.

- Understanding terms/words relating to developing an AR app,
- Describing functions of AR to others,
- Troubleshooting problems of an AR app,
- Explaining why a task is not working on an AR app,
- Using advanced skills when developing an AR app,
- Using an AR app

B INTERVIEW QUESTIONS FOR UX EXPERTS

Grand Tour Questions

Q1 How would you expect to create the AR content using the system?
Q2 How would you expect to design an IoT Device using the system?
Q3 How would you expect the AR content to interact with a physical IoT Device?

Representative Task 1: Creating a story with AR and IoT components.

Q4 If you have a particular story in mind, how would you expect for the system to understand your storyline? (e.g. Programming, write and scan so the system understands).

Q5 What input modalities would you want to control the AR content? (Voice, text, gestures, etc.)

Q6 When using multiple phones, how would you expect each person to see the AR and IoT content?

Q7 If there are multiple users, who should control the AR and IoT content? Should everyone control everything or everyone control something?

Representative Task 2: Creating an interactive workshop for students to use IoT devices and AR characters to complete a given set of tasks.

Q8 What input modalities would you want to control the IoT Devices?

Q9 What activities can you think of for an interactive workshop like this?

Q10 How would you expect to create the activities for the workshop? Should workshop attendees be responsible for creating all parts or instructor? Both?

Representative Task 3: Creating a lesson plan for students to learn about designing IoT Devices, learning with physical computing devices, or other areas.

Q11 Do you think a system like this can be used to create a lesson plan for education modules for high school or middle school students (Chemistry, physics, computer science lessons)?

Q12 Can you comment on the complexity of the education module that has to be taught using this system (i.e. how easy or difficult do you think the task should be set up so the students are motivated, but still challenged)?

Q13 Should the challenges be open-ended (i.e. should the teacher provide direction, but allow the students to come up with a final solution,) or close-ended (i.e. the teacher tells the students to create something and they try their best to replicate those instructions)?

C INTERVIEW QUESTIONS FOR TEACHER

- **Grand Tour Question**: What would you say your teaching style is?
- How do you employ these strategies/techniques in your Academic Classes vs. in your Challenge classes?
- Would you say your classes are more teacher-centered or student-centered? Does this change between your Academic and Challenge classes?
- What do you think are the main challenges facing your students with respect to their education right now?
- How are you planning to teach your students about chemical reactions? How long do you anticipate this lesson to take?
- How do you anticipate your students' reactions to your lesson?
- What technology are you currently utilizing in the classroom?
- Tell me what you know, if anything, about the term "Augmented Reality?" (E.g. Pokémon Go)
- How do you think placing virtual content in the physical world can be used in the class room?
- Tell me what you know, if anything, about the term "Internet of Things?" (E.g. Network connected printer and PC, cell phone connects to car speakers, GPS, etc. via bluetooth).
- If so, how do you think IoT can be utilized in the classroom?