EVALUATING AUGMENTED REALITY TOOLS FOR PHYSICS EDUCATION

by

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ABSTRACT

While we are in the midst of a renaissance of interest in augmented reality (AR), there remain a small number of application domains that have seen significant development. One domain that often benefits from additional visualization capabilities is education, specifically physics and other sciences. This dissertation presents the results of interviews with secondary school educators about their experience with AR and their most desired features. Three prototypes were created which were used to collect usability information from students and educators about their preferences for AR applications in their physics courses. Additionally, we introduce the concept of Environmental Integration, a novel method of defining mixed reality applications based on three properties: Visualization, Input Fidelity, and Spatial Understanding. Several examples are presented to illustrate different levels of environmental integration. The results of the studies conducted point towards interesting areas for further exploration for AR content creation for physics education.

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CHAPTER 1: INTRODUCTION

Augmented reality (AR) is defined by Azuma [5] as a variation of virtual reality (VR) where rather than presenting a fully-synthetic environment filled with virtual objects, the user sees the real world and virtual objects are presented in the same real world space. As technology has evolved, so too have the design of devices for presenting AR content. What was originally presented using opaque VR displays with camera pass-through or sophisticated systems of glasses with special mirrors tethered to a powerful desktop has been steadily replaced with purpose-built, standalone displays with special optics for overlaying augmented images on the real world. Today, even smartphones are used as devices capable of presenting augmented reality information to users. In modern AR systems, objects are placed at specific locations in the physical world using various techniques to track the location of the AR device and the geometry of the physical world simultaneously. Objects can be detected using traditional computer vision methods or Fiducial markers [35], ensuring that the AR content is placed properly in the environment. AR is often used in controlled environments where the space is well known, such as in training for industrial maintenance staff and military personnel.

Recently, the cost of an AR-capable experience has steadily dropped to the point of being considered a consumer product, in much the same way as virtual reality headsets have in years prior. As of 2020, any device with a camera and display is capable of presenting some sort of AR content, though the quality of said content might not be suitable for certain domains. Typically, we can divide modern AR experiences (and costs) into two categories, tablet-/smartphone- based AR and head-worn AR. Tablet/smartphone-based AR leverages smartphones and the sensors contained within (camera, gyroscope, accelerometer) to track the device in space and present location- and scene-aware content on the device to a user. These experiences often use touch-based interaction or marker-tracked objects to enable an interactive experience. They are typically cheaper to build and deploy, and have lower device costs. A smartphone can be purchased for under $100US and provide an adequate experience for an end user. Head-worn AR experiences often use purpose built hardware, such as depth sensor arrays for tracking the environment, laser projectors for projecting content into the user's eyes, and purpose-built, hand-held controllers for interacting with virtual objects. These devices are often expensive, with even the cheapest standalone AR headset costing over $2200US.

As it stands today, however, there is no apparent "killer app" for AR, head-worn or otherwise. From a consumer perspective, there is little incentive to invest in anything beyond smartphone/tablet-based augmented reality applications. There have been a handful of applications that have seen use in the consumer space: Pokemon GO[1] and various AR image-based measuring applications[2][3] come to mind. In the industrial space, the primary application of head-worn AR is training or task guidance. Based on that, we can infer that other "training-like" experiences, such as education, will benefit. Education is one of the areas that often drive exploration when new technologies are developed [14, 45, 58]. Along this same vein, training and education both benefit from the idea of teaching by example. Several military research projects have also arisen that leverage AR, from warfighter perspective to decision-making assistance from command centers [50].

Statement of Research

A non-trivial number of students often do poorly in physics and other introductory courses, which pushes them out of engineering and related STEM fields [22]. One frequently cited reason for attrition in these cases is that physics is the first science course which students encounter that requires

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[1] `http://www.pokemon.com/us/pokemon-video-games/pokemon-go/`

[2] `https://play.google.com/store/apps/details?id=com.google.tango.measure`

[3] `https://itunes.apple.com/us/app/measure/id1383426740`

the application of mathematical knowledge to the real world. Physics courses often emphasize laboratory work as an avenue for reinforcing lecture topics. For concepts like projectile motion, energy, and friction, an in-person lab with physical objects is the perfect medium for illustration. However, concepts like electricity, magnetism, and light waves are not as easily seen or understood from standard laboratory studies. Educators often find creative ways to assist students in understanding these concepts, often using web applications or physical props for assistance. With the advent of consumer grade, head-worn AR solutions like Microsoft's Hololens [55] or the Magic Leap One [46], we can determine if providing alternative methods of presenting lessons to students is beneficial. These newer devices feature inside out tracking and are completely wireless. These two features combine to allow easier setup in new environments and a lower barrier to entry than older technologies. This enables easier distribution of AR content to audiences which may have previously seen the technologies as niche or cumbersome.

A platform is only as useful as the applications which are developed for it. Prospective developers for modern AR platforms would likely benefit from information about their target use cases. Therefore, we would like to take a multi-pronged approach toward developing a series of applications that assist students in physics courses to understand those hard concepts that turn so many of them off to the field overall.

The first step we take is to determine what educators feel they would need to present in software developed to illustrate concepts that they teach often. To ensure ecological validity of the applications we will develop, we leverage the existing expertise of those that currently are responsible for completing the task our application is intending to facilitate. Several existing applications have been developed that tackle this from a VR perspective [62].

Next, we collect the opinions of students to determine what features and interactions they would like to see in applications designed to teach them physics concepts that are often found to be difficult to understand. Most evaluations of education software focuses on pedagogical elements and aptitude tests [8, 58]. What we would like to do is first determine if students would prefer or want to use AR to learn and then, based on the collected preference and feedback, see how they would like the information presented to them.

After collecting this feedback, we can develop a tool to help answer our main questions: ”How does presenting students with physics concepts in AR benefit their learning experience and performance? How does having high levels of integration with existing physical objects affect a student’s understanding of unfamiliar material?” Designing an application to answer these two questions will be reliant on collecting quality feedback in the student and educator studies described in Chapters 3 and 4.

Contributions

We present a qualitative analysis of a prototype augmented reality application for the Microsoft Hololens [55] with a focus on physical science education. We detail the application itself and some of the more prominent features. We then present the results of a series of interviews with secondary school educators to determine some design requirements for prospective applications in their classrooms. Based on a thematic analysis of the collected interview scripts, we present a set of design requirements which would need to be satisfied to meet the laboratory needs of a physics course and helpful comments which may assist developers in making design choices.

We then used the collected feedback from the educators to inform the design of an updated prototype which was used to collect feedback from students on how they would want the application to be changed and molded to fit in their ideal physics class. All elements of the application were evaluated: the presentation of information, the interaction methods, and the concepts selected to be presented. Student feedback was coded and general opinions were collected on what changes and features need to be added to a new application.

This third application, which we call PhyAR2, was designed to answer two more specific questions: ”How does tying AR visualizations to physical objects assist students in understanding new physics concepts? Is there any benefit to presenting concepts in AR with physical analogue items compared to VR with controller-based interaction?” Based on feedback collected during our third study, we conclude that there is some benefit to using physical props for education, but the benefits may be largely due to some degree of novelty with AR, which is difficult to control for.

Dissertation Outline

Chapter 2 gives an overview of existing literature in the AR field pertaining to education software. Chapter 3 details the preliminary work developing a prototype, HoloPhysics, which was used for collecting educator feedback and opinions about potential use cases in their courses. Chapter 4 details a follow-up study with an updated AR application, dubbed PhyAR, which was used to collect qualitative feedback from students and help fine tune what they considered important and their opinions about potential AR use in their physics courses. Chapter 5 details a third AR application study, which covers two concepts, Coulomb’s Law and Faraday’s/Lenz’s Law in deeper detail with a comparison against a virtual reality version of the same application. Chapter 6 includes a deeper discussion of the findings of our work and possible areas for future work. Finally, we conclude with Chapter 7, a summary of the findings of this work. The Appendices include IRB approval letters and questionnaires used in the studies in Chapters 3 through 5.

CHAPTER 2: RELATED WORK

Many researchers and practitioners have published work aimed at determining the usefulness of AR and AR-adjacent techniques for education. Billinghurst et al. give a thorough survey of the AR field overall [9], as well as about AR for education [7]. Their work with MagicBook [8] is seminal work in AR education because it enabled people to see 3D content projected over their 2D books. Other general surveys of the AR field specifically for education have been published [21, 29, 37, 47, 48, 53, 71, 72]. Based on the prevalence of surveys in the field, it is clear that there is a large and diverse amount of interest in applications in education. Some important ideas about augmented reality that are reiterated in the survey papers: augmented reality in the classroom benefits student motivation, contributes to learning outcomes and has a benefit on perceived relevance of subject matter [39].

Akçayır et al. [1] echoed the benefits of improved motivation when testing an AR smartphone application in a university setting. Students who were exposed to an AR smartphone application were more proficient in the corresponding laboratories which the application supported. Students reported experiencing benefits from the visual presentation of information supporting their lab sessions, which enabled them to complete their lab coursework within the alloted course time slot. Feedback from the lab instructors pointed towards an emphasis on discussion of results of lab experiments in students who were presented with the AR smartphone application; in contrast, students in the control group (no AR application) spent the full duration of their time completing their laboratory, preventing them from synthesizing higher level conclusions with their lab partners.

Chang et al. [19] present a survey of existing applications of AR in education, separated into a broad spectrum of fields. These fields include chemistry, physics, geology, and spatial understanding. One section the authors set forth relates to K-12 education. The results of some presented studies point towards AR having a positive effect on learning experiences and increased motivation. Additionally, there were benefits to students who were otherwise struggling academically. SMART, a system developed by Freitas and Campos [34], superimposes 3D models on real time video feeds to be presented to a class of 2nd grade students for a gamified learning experience.

We have, as of yet, seen very little integration of augmented reality tools in real classrooms despite the presence of tools which have been developed specifically with education in mind [7]. LearnAR is a toolkit developed to enable the generation of augmented reality content for desktops using a web cam [3]. It has been used to bring tools for development to a wider audience by abstracting away the complexities of programming by providing a set of resources to teachers which can be used as is. Any application designed to be used by teachers would need to have a similarly low barrier of entry to see any degree of adoption by educators with limited experience with modern technologies.

Dünser et al. [28] created a spiritual successor to MagicBook which used ARToolKit and OpenSceneGraph. The framework enabled students to create virtual books that overlayed on printed textbooks and allowed for some degree of interaction. Results showed that AR was potentially beneficial for teaching electromagnetism concepts. Similar results have been found by Enyedy et al. [30] in the domain of kinematics for primary school students and Estapa and Nadolny [31] for mathematics in secondary school. Other examples of AR education tools exist [24, 38, 64, 65, 67, 70], but for the most part, they all emphasize a smartphone based environment. In this work, we emphasize head-worn AR scenarios in lieu of these tablet-based solutions, which should theoretically perform similarly as they are more feature rich than smartphone solutions.

Bujak et al. [15] discuss the importance of having some physical affordances in the mixed reality environment to improve symbolic understanding. We developed a particular scenario with this in mind, making sure to align virtual objects with a similar anchor in the real world. Dunleavy et al. [27] discussed some of the more complex problems with running classroom scale augmented reality with touch-based devices in different school settings. If physical affordances are not used, the application will likely be more in line with existing virtual reality (VR) experiences like those developed by project ScienceSpace during the 1990s [26, 62]. Salzman et al. [62] presented a thorough list of some best practices in VR conceptual demonstrations throughout the development of their virtual worlds, which illustrated kinematics, electrostatics, and molecular structure.

Perkins et al. [58] developed PhET[1], a well-researched and widely used web-based application for physics education, with other sciences also being featured. Many demos for different concepts are featured on the page as illustrated figures which teachers can use in a variety of ways, including lab assignments, interactive demonstrations, or exploration. A straightforward way to ensure adoption of a new application is to ensure it meets the needs of existing applications and enhances them in some way. Drawing inspiration from PhET, our prototype aims to visualize physics concepts similarly, but with improvements for 3D content and information presentation.

Chang et al. [20] compared multiple models of simulation-based learning and compared them against traditional laboratory learning for physics studies, specifically emphasizing basic optics. Their findings pointed towards students presenting better learning results using simulations than in traditional laboratories, regardless of students' abstract learning capabilities. This piece of feedback allowed us to focus primarily on AR and VR in our last study, as we expected that both would outperform a traditional lecture regardless.

More recently, Radu and Schneider [60] presented the results of a study comparing an AR system using a Microsoft Hololens to a traditional laboratory learning condition in a lab specifically designed to teach students about the design of speakers and how they produce sound. The study was collaborative and had three conditions, one without any AR headsets, one with AR presenting

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[1] `https://phet.colorado.edu/`

overlays of sound on a fixed system, and one with multiple stages of detailed information about the speakers presented over time. The results of the study pointed towards better understanding of the specific concepts in the lab and improved self-learning by the students during the lab but did not find a large difference in relative learning gains between the groups. There was a higher level of engagement found within the students who were presented the laboratory in AR. Lastly, they reported that students enjoyed the visualizations.

In the domain of AR collaboration, Villanueva et al. [69] presented an AR-based teaching and learning tool for collaborative AR. The goal application was designed to allow a two-way connection between students and teachers, as well as between collaborators in a cloud-based environment. Users of the system, dubbed Meta-AR-App, were able to author changes to AR content and push changes to a cloud server for distribution to other users.

Kang et al. [42] developed ARMath, which created a touchscreen-based AR system through a participatory design process leveraging the expertise of practicing educators and their prospective students. The resultant system could allow for on-screen and tangible interaction with real world objects to assist in STEM learning for early learners. Some key takeaways from this work are that everyday objects are useful tools for improving learning in mathematical settings, and that children did not prefer tangible or virtual manipulative items over one another.

Ashtari et al. [4] presented a list of barriers to AR/VR authoring that include but are not limited to lack of design guidelines, frequent changes in technology, expensive hardware, and difficulty with evaluating user behaviors. There are others listed within the publication, but we emphasize these three because they were the barriers we most frequently ran into. First, the lack of design guidelines and best practices led us to explore what educators and students would want to be presented with in an AR application, which we discuss in Chapters 3 and 4. The frequent changes in technology and software toolkits also caused a number of issues throughout our development process, with the hardware we selected to use for our studies being the frequent source of user experience issues relating to interaction shortcomings. Lastly, user behaviors are difficult to predict, as some participants were simply unable to replicate proper inputs or were not able to properly wear the AR hardware we used in our studies.

Ferdous et al. [32] found that there were some significant improvements in learning results when presented with information in AR in a physiotherapy context. Huang et al. [36] found that VR was better for visual presentation of learning experiences than AR, but AR was better for auditory experiences. Though these findings were likely specific to the AR and VR configurations selected for the study conducted, we also consider these results when discussing our study 3, detailed in Chapter 5.

Saidin et al. [61] present a meta-analysis of the advantages of using AR for education and specific educational subjects which have existing research in their domain. The authors point out that there are benefits to using AR presentation for educational purposes, such as being able to present invisible concepts like chemical bonds with detailed visualizations from different viewpoints and at different scales. This brings both micro- and macroscopic concepts to a scale that is more approachable and consumable for learners. The authors also reference work by Klopfer and Squire which concluded that a mixed reality lesson about environmental science was positively received by the students.

Further existing work by Coffin et al. [25] shows that augmented lectures are a viable method of encouraging students to remain interested in more esoteric subjects within their courses. Coffin et al. developed a system using a projector, camera, and desktop computer to create augmented lectures for students in the form of videos captured from the real world with augmented content added to the lecture after it has been completed. The system uses an ARToolkit marker to determine properties of real world objects which will be tracked in the videos. An additional marker can be used for specifying where interactable flat surfaces lay within the real world. Once initial setup is complete and a lecture can be recorded and then annotated using object tracking and widget overlays. The video can be interacted with on a frame-by-frame basis by both the creator and the audience. The system is designed to be low cost, not require complex tools to distribute to students, and not require significant processing power to create or consume.

Cai et al. [16] conducted a study to determine the effects of using natural interaction for teaching physics to eight grade students. The authors developed an application using a Microsoft Kinect which then was used to overlay magnetic fields and virtual magnets in a real time camera feed which is then presented back to the user. The study compared a control featuring a traditional teaching environment with textbooks against the natural AR application to determine if there was a difference in learning behaviors, as well as their perceptions of the AR modality. The study found that there were differences in performance on graphically presented test questions between the two groups, but no differences on long term conceptual understanding (turning observations into laws). However, feedback collected from the students pointed towards increased engagement and motivation due to the novelty of the AR-based condition.

Cai et al. [18] set out to determine the effects of AR learning on students self-efficacy by presenting a novel wave-particle application. A longitudinal study was conducted comparing a Flash application to an AR application to teach the photo-electric effect. A group of high school students were presented with short 10 minute vignettes once a week for four weeks. Pre- and post- study questionnaires formed the bulk of the feedback collected from the study. The results of the study pointed towards positive benefits in self-efficacy, higher level cognitive skills, greater understanding of concepts, and higher motivation in students who were presented with the content in AR instead of the Flash application.

Chen [23] conducted a qualitative evaluation of a mixed physical/virtual learning application which featured models of basic amino acids from an organic chemistry course. Participants were free to switch between interacting with a physical model of a molecule and a Fiducial marker tracked by a webcam and visualized on a laptop display. Participants reported preferring interacting with the physical model, but also interacting with both physical and marker simultaneously. Participants reported experiencing some benefits to the dynamic visualization that the marker and display provided, further implying that there were use cases that would benefit from being able to control the presentation with different displays and information overlays.

Santos et al. [63] performed a meta-analysis of existing augmented reality learning experiences (ARLE) which were presented in published work from 2005 to early 2012. The authors determined that it is important for researchers to evaluate potential learning benefits and the usability of the prototypes they develop. Specifically, the authors found that evaluation metrics are inconsistent across different domains, with many of the surveys and performance metrics not being validated. Three affordances are presented as inherently present in AR specifically for learning scenarios:

- Real World Annotation - the ability to overlay text and symbols on the real world .
- Contextual Visualization - the ability to display virtual content when certain real world context/state information is present.
- Vision-haptic Visualization - the ability to present an embodied virtual object in the real world using a tracked object or marker.

The authors covered a total of 87 existing ARLEs and presented different dimensions for arranging their properties, including display modality (mirror vs. glasses/see-through), content creation method, evaluation techniques, and annotation method.

Barma et al. [6] also discuss the impact of *digital natives* being used as the study population for the evaluation of these AR applications. The authors developed an AR-based game for iOS tablets which presented an electromagnetism lesson but in a gamified setting, which they called Parallel. Students are presented with a 3D view of vectors, trajectories and fields of the elements in the virtual world in an effort to better reinforce the concepts. The game itself is an exploratory puzzle game with puzzles that leverage the content of a college level physics course to support the illustrations presented to the students. The authors found that students benefited from being to ”see instead of imagining” their lessons, especially in an interesting, involving scenario like the puzzle game presented.

Breisinger et al. [13] developed LEMMA, which is a multimedia education system for authoring interactive 3D content without any experience in content development or programming. The authors determined that there were potential learning benefits to the VR-like system they presented, but also noted that there were shortcomings of their study due to single exposure.

Based on the existing body of work, we choose to focus on determining how we can fit head-worn AR systems with varying degrees of environment integration into a classroom. We focus primarily on physics as our main subject due to the direct connection between most physics concepts and the physical world around a learner. To ensure our system would best suit potential users, we begin by asking the group most well versed in day-to-day learning procedures: educators.

CHAPTER 3: DETERMINING DESIGN REQUIREMENTS FOR AR PHYSICS EDUCATION APPLICATIONS

The purpose of this work is to discern what application features would be most important to educators and students who would be using AR physics applications. With head-worn AR being a newer medium in the consumer space, there are no known existing solutions which emphasize physics concepts in this domain. We developed a prototype application for the Microsoft Hololens to illustrate a handful of concepts which could be used as proof of concept for demonstration purposes. Our goal was to gather information about what educators considered to be important and interesting features which would facilitate the learning process for their students. What follows is some background about the nature of augmented reality, a description of the application used in the study, and details and results from the conducted interviews.

Environmental Integration

There have been various attempts to extend and classify different experiences leveraging AR/VR/MR since Sutherland's seminal 3D headworn display demonstration [68]. One of the more prominent examples is Milgram's Mixed Reality Continuum [56], which treats AR and VR as opposite ends of a one-dimensional axis. More recently, there have been attempts [10, 40, 43, 52, 57] to provide greater fidelity to the continuum to better encapsulate interaction components and *spatial understanding*, the degree to which the device provides information about the environment to the application.

Other work [54] makes no attempt to classify a system holistically, but instead specifies properties along multiple dimensions as a method of isolating different components for analysis. For the purposes of this work, we utilize our own method of defining properties of an augmented reality application based in a similar, multi-dimensional manner. We refer to this set of properties as *environmental integration*. In simplest terms, environmental integration refers to the degree to which virtual objects are integrated with the real world, how they are presented in the headset/device, and how the user interacts with them. Environmental integration is divided into three different dimensions, each ranging from low to high, which we define in a method similar to the classification criteria specified by [57]:

- **Visualization** - The fidelity of the content being presented. This property is determined by a combination of physical display properties (resolution, field of view, transparency), presence of real world visualization (via passthrough or transparent optics), and virtual environment properties (density of virtual content vs real world content). An experience with high visualization would feature wide field of view, large amounts of virtual content, and the capability of viewing the real and virtual world without distortion simultaneously.
- **Input Immersion** - The degree to which natural user interactions are used. Low input immersion would indicate that there is a clear disconnect between how a user would affect a virtual object in their environment. This can be due to the use of controllers or unreliable tracking. Poor tracking would be considered low input immersion, and controllers would be considered medium. A higher input immersion interface for an AR experience is one which allows for unencumbered use of the hands to interact with physical objects.
- **Spatial Understanding** - The amount of real world information being used to anchor and influence virtual objects. Real world information in this case can include the position of Fiducial markers in space (medium spatial understanding), the position of surfaces in the real world, and the extraction of known objects from a spatial mesh (high). An experience with a high level of spatial understanding would be able to recognize, segment, and track

objects and surfaces of interest from a dense, realistic physical environment.

An ideal AR experience would feature high measures along each of these dimensions, as any application which met that baseline of performance would demonstrate near seamless interaction with the real world. For the convenience of the reader, each application developed in this work will specify low, medium, or high for each of these dimensions when referring to environmental integration.

HoloPhysics

Our prototype application, HoloPhysics, was developed using Unity3D[1] and the Mixed Reality Toolkit[2] for use with the Microsoft Hololens [55], which is depicted in Figure 3.1. The Hololens is a purpose-built, standalone AR device which features see-through holographic lenses which reflect light from miniature projectors into the user's eyes to present images over the real world within a 34 degree field of view. The device supports gaze based interaction and a pinch-to-grab gesture for clicking on objects in the AR environment. It features inside out tracking to both generate a spatial map of the environment and localize the headset within the real world, allowing users to interact with world-aligned virtual objects. We leverage this tracking to properly place virtual objects in the real world.

HoloPhysics consisted of three self-contained demonstrations for illustrating a specific concept using virtual objects in the physical space. Each of the demonstrations was based on a concept from a high school physics class. The concepts which were emphasized in development included electrical fields, elastic collisions, and parallel circuits. The demonstrations had varying levels of

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[1] `https://unity3d.com/`

[2] `https://github.com/Microsoft/MixedRealityToolkit-Unity`

Figure 3.1: Microsoft Hololens, the device which makes up the experimental setup for the study. Photo credit: Microsoft

environmental integration.

Electrical Fields

A three-dimensional grid of vectors is presented to the user, along with an arbitrary number of point charges. The user can add or remove the point charges, as well as translate them in space. The grid of vectors updates in real time, presenting the charge at the point in space according to Coulomb's Law. An example image of this demonstration can be seen in Figure 3.2. This visualization features low environmental integration. The user can move the points freely through the any real world objects without influencing the presented content.

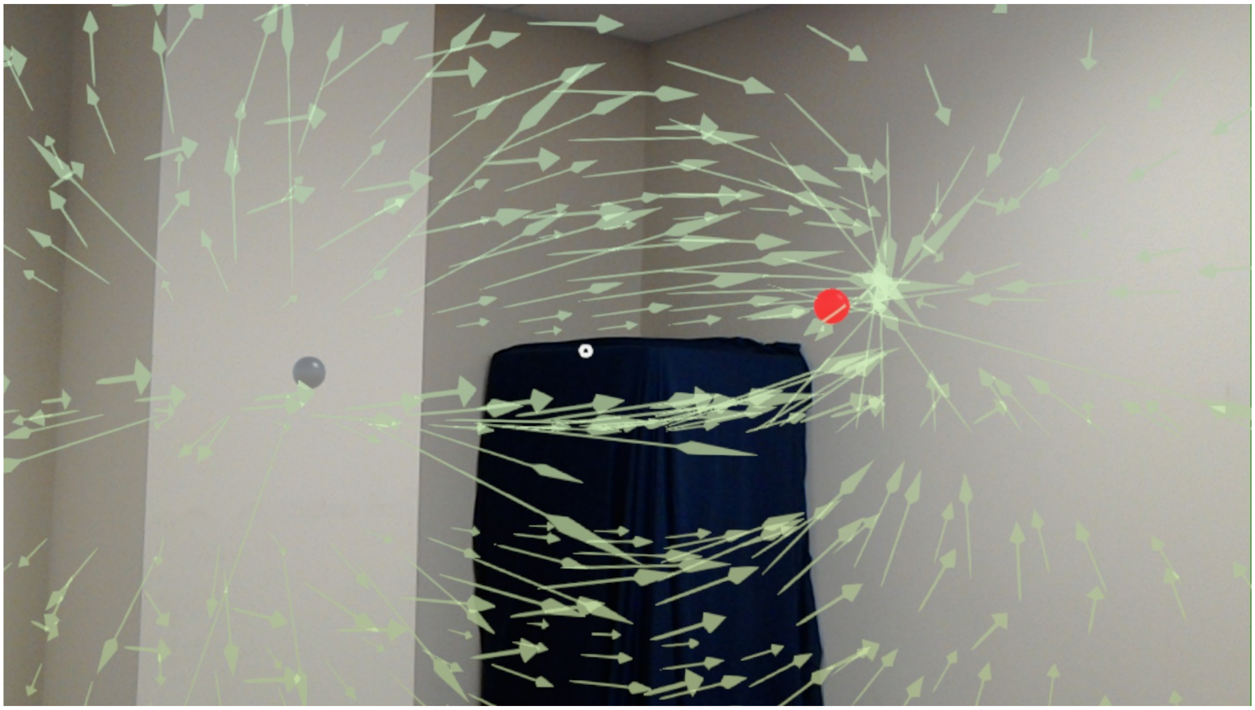

Figure 3.2: Capture of the AR headset presenting a point charge electrical field as an illustration of Coulomb's Law.

Elastic Collision

A ball is presented to the user along with a flat panel with a description of the *coefficient of restitution*. Physical properties of the ball can be altered by the user by manipulating sliders on a 2D canvas, including the coefficient of restitution, initial height, and friction of the surface of the ball. The ball resets to an initial position whenever the initial height is changed. The ball interacts with the spatial mesh generated by the Hololens, which provides approximate collisions with real objects in the environment. The material properties of the real objects are ignored and treated as solid. A variation of this demonstration was also developed which features a ramp with adjustable angle. The two demonstrations differed in that one featured a virtual object interacting with only physical objects, and the other interacted with both physical and virtual objects. The elastic col-

Dummy text about how ramps do things to energy.

Figure 3.3: Capture of the AR headset presenting a ramp with a bouncing ball, which interacts with the spatial mesh captured by the Hololens.

lision features low environment integration aside from the collisions with the spatial mesh. An example image of this demonstration can be seen in Figure 3.3.

Parallel Circuits

Users are presented with a parallel circuit visualization of the lights in the room they are in. A virtual light switch can be toggled on or off and the corresponding light and circuit will be switched on or off, respectively. The positions of the virtual lights and light switches were manually calibrated and anchored by a proctor to align corresponding real-world lights and light switches. An example image of this demonstration can be seen in Figure 3.4. This demonstration was meant to represent what could be possible when a device had high levels of environmental integration and

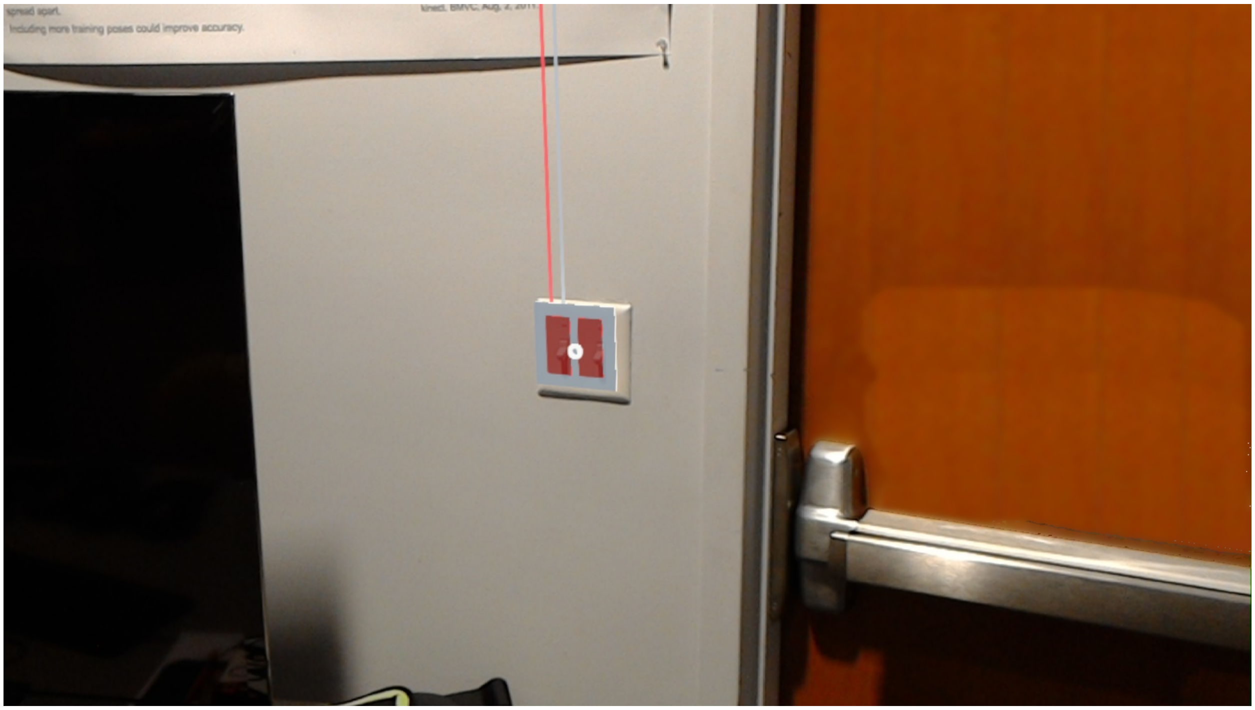

Figure 3.4: AR capture of the headset presenting a light switch which overlays a real switch and shows the parallel circuits running to the ceiling lights.

the application was able to appropriately recognize the state of objects in the environment.

Educator Interviews

We conducted semi-structured interviews of six secondary and post-secondary science educators to determine what utility, if any, they can see in the AR prototype we developed. Secondary school covers students aged 11-16 in most countries, while post-secondary or tertiary school makes up what is typically called college and university education. Educators were recruited from different secondary schools in two local school districts and via word of mouth. Demographic information from the interviewed educators recruited can be found in Table 3.1. The educators' ages ranged from 26 to 59 ($M = 40.5, SD = 13.8$) and experience ranged from 1 to 31 years

($M = 13.0, SD = 11.6$). Three of the six educators were female. Interviews were recorded and took between 30 and 45 minutes to complete, depending on the depth of discussion between the interviewer and study subject. Two of the educators, T3 and T5, provided limited information in comparison to the other four. They gave direct answers to the questions asked of them but did not provide deeper feedback than the main questions asked by the interviewer. The primary focus of the interviews was to determine what kinds of features would be most important to encourage adoption of AR as an alternative or supplement for physics laboratories and lectures from an educator's perspective. Information gathered from these interviews would inform the design of future prototypes to be presented to students directly. In this way, these interviews served as background data collection in answering both of our main research questions:

- How does presenting students with physics concepts in AR benefit their learning experience and performance?
- How does having high levels of integration with existing physical objects affect a student's understanding of unfamiliar material?

Interview Protocol

The interviews followed a specific script. First, educators were asked the following questions:

- Have you ever used an AR/VR application? If so, was it for educational purposes?
- Have you ever used PhET or another physics concept demonstration application?
- What are some examples of physics labs that you run with your students to reinforce concepts which have been introduced in lectures?

These questions were selected to provide adequate coverage of the background of the participants being interviewed, such as their experience with AR/VR, their experience with teaching with software, and their normal teaching habits. The interviewer was free to ask follow-up questions related to the answers provided to the predefined questions. Interviewees were then presented with a demonstration of the HoloPhysics prototype, and then were encouraged to explore the demonstrations firsthand. After being presented with the prototype, the interviewee was asked another set of questions related to their experience with the prototype and what features they consider mandatory in any application they would use in the course:

- Do you feel that an AR tool like HoloPhysics would be beneficial to your students? If so, in what ways?
- What sort of features do you think an application like HoloPhysics would need for you to use it in a classroom setting? Can you think of any other settings where it would be useful?
- How would you employ HoloPhysics in your own physics courses, assuming it included your requisite features?

Interviewees were then asked for any further comments or considerations they deemed relevant.

Table 3.1: Demographic data and teaching experience of the interviewed participants.

Participant	Subject	Age	Experience	Grades Taught
T1	Kinesiology	52	31	9-12
T2	Physics	45	15	10-12
T3	Physics	26	1	10-12
T4	Chemistry	59	21	10-12
T5	Physical Science	35	7	10-12
T6	Physics	26	3	7-8

Data Collection and Analysis

Data collection was done with a pen and paper and voice recorder. Overall, a total of 3.5 hours' worth of recordings and notes were collected and transcribed for thematic analysis by the authors [12]. After an initial set of themes were determined, the authors iterated over them to determine if any themes could be merged or others need to be generated. We found that themes were distinct from expected responses to the set of questions asked, as any elaboration requested by the interviewer tended to provide more detail than the original questions. We organized these themes into two overlapping sets, those which were preliminaries connected to the individuals' experiences or teaching style, and those themes which were directly related to the demo presented and recommendations emerging from them.

Findings

In this section, we present recurring themes which were present in the interviews. We also lay out a handful of interesting comments and requests for features which were unexpected. These themes included *Novelty*, *Reinforcement*, *Exploration*, *Variable Presentation*, and *Collaboration*. Specific details about these themes can be found in Table 3.2. *Reinforcement* and *Exploration* were derived from the two types of labs the educators discussed frequently.

Preliminaries

Of the six educators interviewed, only two had any experience using virtual or augmented reality in their classroom, solidifying that there was *novelty* to any application presented. One had used it to play Pokemon Go, a smartphone based application, which features optional augmented reality features. One educator stated that they have used tablet-based AR for exploration in their chemistry

Table 3.2: Codebook used for thematic analysis of educator interview transcripts.

Code	Description	Example
Novelty	Educator states that the AR interface is new, different, or will encourage students to remain attentive.	”Kids are engaged in technology. To have a learning experience that fits within the same environment would help keep them engaged in the concepts.”
Reinforcement	Educator discusses potential use cases specific to assisting students between using lectures and labs to assist in understanding already presented concepts.	”This application allows people to do more than just looking at a video.”
Exploration	Educator discusses use cases involving using AR device as a method of encouraging individual exploration by students on newer concepts.	”Labs are used to reinforce subjects at the end of the subject. At the end of the block of lectures, they run the related lab.”
Variable Presentation	Educator discusses using multimodal presentation of information, with mixed physical/virtual or concept/concrete mathematical representations.	”Having something that allows both basic introduction into the subject matter, but also allow students who are more advanced to be able to play with the numbers.”
Collaboration	Educator specifically mentions collaborative tasks for educator-student or student-student scenarios.	”I would like to see students play around in different stations and then come together and discuss what they learned.”

class:

> *”We had stations and at each station they had to use AR and something would pop up and they would have to go to a reference that would show them a diagram of something.” (T4)*

This type of augmented reality experience remains the most prominent in today’s consumer electronics space. Mobile device developers like Apple[3] and Google[4] have been pushing out more software development kits (SDKs) to assist in the creation of similar experiences. It can be dif-

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[3] `https://developer.apple.com/arkit/`

[4] `https://developers.google.com/ar/`

ficult to recruit anyone with experience in the domain of AR, especially in non-technical fields, which speaks volumes about the adoption rates of modern AR devices or lack thereof.

All six educators interviewed had used PhET or a similar web application in their courses to augment their lectures or as student activity for reinforcement. The degree to which the web apps were used in their classroom varied, though the consensus was that they were an important component:

> *"We use them a lot. I use them a lot in chemistry to teach the physics of atoms. There is PhET and then there is one called Collisions*[5]*. It's a game based. It takes kids from building an atom to doing acid-base reactions." (T4)*

> *"I use PhET simulation constantly in my classroom. I use them for lecturing purposes and for activities. My students just submitted a lab activity... that used a PhET application graphing position, velocity, and acceleration." (T6)*

The emphasis of the laboratories themselves varied depending on the educator. Most physics labs were carried out to *reinforce* concepts after a lecture had been completed on a new subject. However, there were also labs which are carried out prior to the introduction of the subject:

> *"I am a big proponent of inquiry based learning. I can give them the time to discover new concepts from early on." (T4)*
> *"...Most of the time it is to reinforce but a lot of the time it is before and after the lectures about the subject. Often we will run a simple exploration, and the second lab would have more details based on what they learned." (T5)*

This type of *exploration*-based lab is more common in advanced or honors classrooms.

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[5] `https://www.playmadagames.com/`

As it pertains to distance learners (virtual school)[6], T2 reported that students were not asked to carry out any laboratories, to the best of their knowledge. T6 discussed the importance of presenting information in a way that can be scaled appropriately for different populations, thus the theme *variable presentation*. A significant portion of their students were not as academically proficient as other students or struggled with language barriers.

> *"Often times, students can understand concepts and application of concepts, but struggle with reading or understanding the language. Providing students with as many alternative forms of instruction, such as simulations, other visual demonstrations or hands-on activities, helps students to still see and understand information despite learning disadvantages." (T6)*

Post-Demonstration

Of the three scenarios presented, all six educators were most impressed by the electrical field scenario. T6 reasoned that this would be an extremely useful demo for interacting with concepts from lectures in a "hands on" way, which is not exactly possible with non-visible things like energy or fields. Educators saw *novelty* in the presentation of something that is often presented as a 2D figure on a screen or printed book in interactive 3D. The bounce/ramp demo was the least preferred in its current state due to the relative simplicity of the scenario and the ease of accomplishing the same task trivially with a physical ball and stopwatch.

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[6] The virtual school referred to by T2 is Florida Virtual School, (FLVS), which is an optional full- or part-time online alternative to in person education that is available as a free alternative to public school attendance for Florida residents.

How Students Benefit

The first of the post-demo questions was about whether the prototype application or similar application would be beneficial to students. All the educators believed that there was some benefit to any of the scenarios but not uniformly. One educator detailed interesting ideas for their classroom:

> *”This could be great or center activities where students are interacting with concepts from lectures in hands on ways. Students usually have a difficult time grasping concepts from physics at first because they cannot see force or energy or fields, they only see their effects. Having some sort of application where they could see the electric and magnetic fields and how they change depending on the position of a charged object would be great. If there was a way [in the ramp demo] to add or show the angles and force vectors or velocity/acceleration vectors while an action is occurring, that is what is usually difficult to teach and would be extremely useful.” (T6)*

Two other educators repeated similar sentiments in the presentation of vectors to present forces, velocity, and acceleration.

One educator felt that instead of having each student wearing an AR headset and interact first hand with the AR application, asking educators to wear the device could be a better alternative:

> *”You could record this as a lecture and then present it to students at another time. Treat it like an augmented lecture.” (T4))*

It should be noted that this idea stemmed from the belief that cost was a large factor in the adoption of any application in the classroom. The current state-of-the-art AR headsets are priced well above $1000, far more than the lab budget for many departments at local high schools. This made it difficult for this educator to consider applications that emphasized investing in multiple devices, $50,000 for a classroom of 30. They also brought up a point about the chaos of a school classroom:

> *"So if I had 30 students and I had them all working in the same space, as in a traditional high school, that's going to be an issue." (T4)*

Requested Features

Educators responded with a wide array of features which they believed would need to be supported by the application to use it in a classroom. Most recommendations came in the form of specific concepts in addition to the ones which were presented to them in HoloPhysics:

> *"Things like Bernoulli principle and the flow of air around a golf ball... Rotations are another thing I am thinking about. In sports science, we are often looking at the movements of limbs in three dimensions, which can be difficult to visualize different forces." (T1)*

> *"It would have some pedagogical benefit at least as an add-on to build something like the light switch demo. Students often ask, "why is this relevant to me" when discussing a number of subjects." (T2)*

> *"Marine science might benefit from things like cohesion and adhesion, and attractive forces in fluids." (T3)*

> *"What I would like to do is simulate a rocket launch and be able to visualize all the kinematic equations as the rocket is going up. It would be nice to have a little blackboard to see how the equations are manipulated in relation to time. (T4)*

> *I think it would be nice to teach math and physics simultaneously, instead of separately as we teach it now. I would like students to be able to discover the equations on their own during an inquiry style lab. Having the ability to be able to switch between a detailed and simplistic view would be beneficial. In the projectile motion example, adding the ability to manipulate multiple parameters in real time, or visualize multiple projectiles at once and compare in real time. There are also safety and classroom management issues which occur in real laboratories." (T4)*

> *"I think having something demonstrating the relationship between velocity and acceleration would be very useful. Students also tend to struggle with balancing chemical equations. So maybe something where they could move molecules in a reaction around to balance the equation. I do something similar just using pom-poms, but an AR application where they could see actual atoms and work with them would be sweet. Thermodynamics ... would definitely be useful." (T6)*

The other frequent feature request tended to be for the optional presentation of force diagrams or a blackboard which could be used to observe numerical changes while a lab is being simulated.

Course Integration

Educators had broad ideas about how they would employ the physics applications in their course curriculum.

> *"In my traditional classroom, I think what I would do is use it to demonstrate certain things and record lectures. I would probably do small groups where I had 2 or 3 students working together where they could use it in an inquiry like state. I would like*

> *to see students play around in different stations and then come together and discuss what they learned." (T4)*

> *"I may use it for a lab where students must complete certain tasks using the application and then answer critical thinking questions about it. I may use it in centers, where at each station kids must interact with a different feature. I might use it for small group instruction, where kids are doing or seeing concepts as I reinforce the lesson. I think this would be pretty versatile for educators to use." (T6)*

Educators felt that *collaboration* in interaction and problem-solving within small groups, as in traditional lab groups, would continue to be important regardless of presentation medium.

Design Implications from Teacher Interviews

In this section, we present lessons which were learned from the study which may influence design implications for future head-worn AR applications. While there is an existing body of work in tablet/smartphone-based augmented reality education applications [21], the content that can be presented using head-worn AR differs. Based on the themes we discovered, and comments compiled during our evaluation, we have come up with a collection of recommendations.

Augment the Visible

Consensus in the interviews was that the simple ball visualization was not particularly useful for classes as implemented in our prototype. Educators would prefer to see force diagrams and vectors added to the scene to assist in understanding why objects moved the way they did. This visualization extends across multiple physics subjects, from kinematics and projectile motion to concepts like electrical and magnetic forces. Some examples of best practices for where to place overlaid information were presented by Santos et al [63]. Augmenting the presentation of information in this way speaks to the *novelty* and *variable presentation* themes which were present in the analysis.

Visualize the Invisible

A frequently mentioned recommendation during the interviews was to emphasize subjects and concepts that do not have trivially executed laboratories. Concepts such as electricity and magnetism which are not easy for many students to grasp at first exposure. Normally, students are limited to computer-based simulations or figures from textbooks for illustrations of these concepts. By presenting them in augmented reality in real space, it is possible to reinforce the concepts by providing spatial integration in some way, like in the light switch demo.

Similarly, one of the educators, T2, discussed a specific lab which they carry out to visualize resonance frequencies from sound waves. The setup for this type of lab is difficult and the visual feedback is only present if everything is set up perfectly. This is the type of lab that benefits from the guidance and presentation possible with in AR. Additional examples of bringing visual details to the invisible that were considered useful to the educators were adhesive and cohesive forces in fluids and optics. This recommendation is influenced by the *novelty*, *variable presentation*, and *exploration* themes.

Present Both Concepts and Calculations

Educators frequently pointed out that students learn at different levels and benefit from different presentations of information. Multiple educators pointed out that most students benefit directly from seeing concepts in an informal way prior to delving into the math for *exploration* or *rein-*

forcement. In this way, we would recommend supporting the presentation of both concepts and calculations to students within the application. Some students may prefer to directly manipulate the equations and watch changes, while others like to drag and drop items. PhET implements this idea in many of the simulations it features [58]. Illustrating concepts in the way it was done in the three scenarios presented to the educators is good as an introduction to the concept, but many students benefit from seeing the underlying calculations which influence the physics simulations. The dual mode presentation of information is not novel, as it exists in existing tablet-based applications [41]. The option to disable or enable components echoes the theme of *variable presentation*.

Enable Collaboration and Demonstration

One educator made a strong case for also developing tools that would enable lecturers to present augmented content to students in the form of first-person demos. Their argument was primarily that the high cost and potential fragility of the hardware would dissuade them from handing the device off to students to use without supervision. Instead, they presented the case that the educator would make the best use of the hardware as a demonstration tool. Other educators stated that a handful of students at a time should be working with a single device or single space as a shared experience. Augmented reality enables collaboration via remote video playback of the live feed from the headset or by presenting a shared experience to multiple users in distinct spaces. Applications which are developed with classroom use in mind should consider which specific use cases they would like to support, be it a lecturer's role or one where multiple students are interacting with a scenario simultaneously, as they often do in labs. For instance, if the application is intended to support multiple users, ensure that all students are presented with the same study content and that the state of the content is uniform throughout the experiment.

It is also important to consider the classic lab station design which has been a staple of secondary and post-secondary schools. There are often far fewer lab stations than there are students, so students must take turns using lab equipment. In the same way, students would be expected to share AR headsets at different stations as described by multiple educators in the previous section. Integrating support for experience sharing among students, that way each student can observe an experiment or concept at their own pace would be beneficial. An example of this would be allowing students to rerun a rocket launch with the same parameters and random seed to ensure consistent data in their lab notes.

Discussion

Upon reviewing the recommendations presented in the previous section, it is clear that many of them are not limited in scope to head-worn AR. In truth, the best practices and supported features would be similar on a tablet or touch screen device. Many existing education software packages already include features that satisfy some of them. One interesting thing that was uncovered was how much crossover there is between physics and other high school science courses. Many educators are saddled with the responsibility of teaching multiple courses and thus their perspectives and responses were not limited to a single subject. PhET also features a broad selection of concepts from different disciplines.

Limitations and Future Work

One clear limitation with the study is that it does not acknowledge the other side of the pedagogical equation: the students. While an educator's intuition is sufficient for determining how to structure a course and develop an application, students' perceptions and performance when evaluating a new method of presenting information are important details. Continuing this research, we would like to incorporate more of the recommended concepts and the presentation of the backing equations for the labs in an updated HoloPhysics prototype and evaluate it in a high school classroom.

Educators also could benefit from improved authoring tools for content. Though most of the educators interviewed considered themselves non-technical, they did have ideas for novel labs. We would also like to develop tools to allow educators to construct their own AR science experiences which they can tailor to their specific course curriculum.

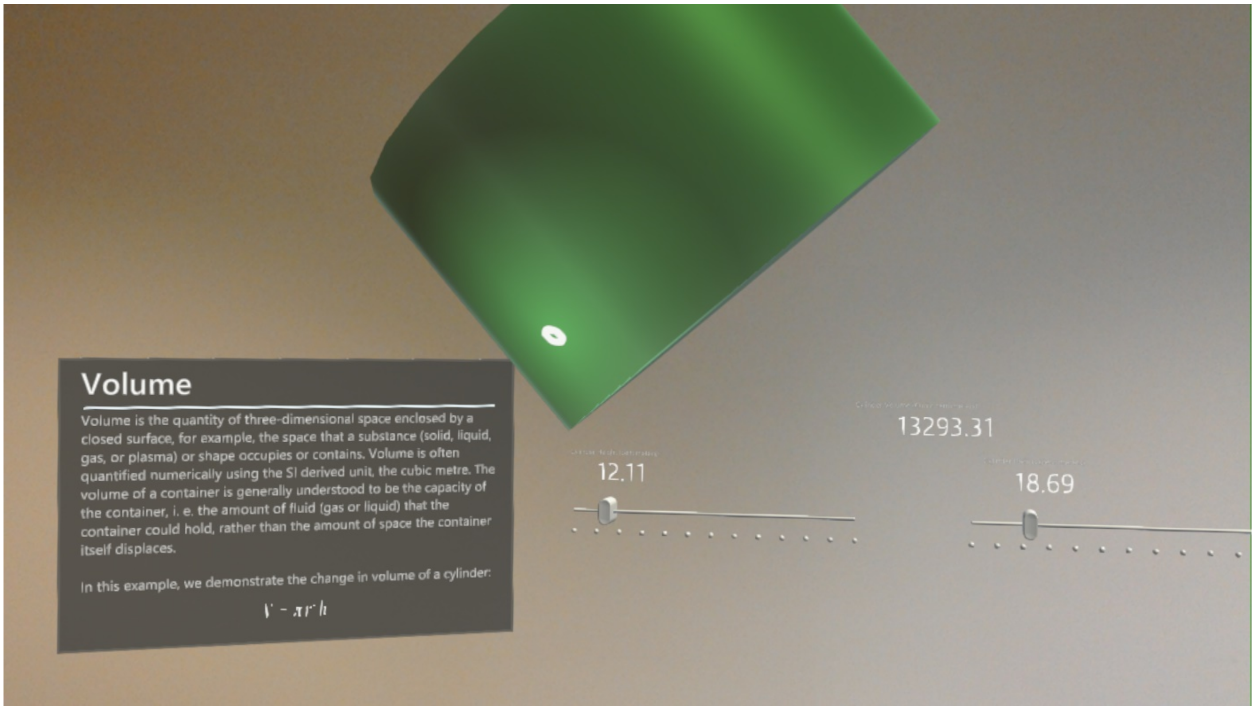
In this initial work, we presented the results of a qualitative analysis of design requirements of AR physics applications using head worn devices. Interview data was collected based on a series of questions detailing experiences and opinions from a prototype Hololens application for physics students. We uncovered a set of five relevant recurring themes: *Novelty*, *Reinforcement*, *Exploration*, *Variable Presentation*, and *Collaboration*. The responses gathered point towards a healthy set of features which should be supported to encourage adoption of any future applications in this domain.

CHAPTER 4: PhyAR: DETERMINING THE UTILITY OF AUGMENTED REALITY FOR PHYSICS EDUCATION IN THE CLASSROOM

The results of the first study pointed towards clear areas for improvement in the HoloPhysics application. Educators pointed out that they wanted to see more concepts demonstrated, so that was one of the most important things we wanted to address for them. We felt that we needed to collect students' opinions and preferences to complete the picture of what role AR could fill in a physics classroom. To do this, we first carried out a focus group with a group of seven students to collect baseline thoughts on possible use cases. We then performed a qualitative study of an updated version of HoloPhysics, which we call PhyAR, to determine how well students can use the application and how they responded to a new method of presenting new concepts.

PhyAR: Updating HoloPhysics

Based on the feedback collected from the educators, we made several updates to our prototype. The most significant of the changes came in the form of conceptual explanation windows in the application, changes to allow for easier navigation between each of the demonstrations, and the addition of four new demonstrations: Ramp Kinematics, Volume, Magnetic Fields and the Doppler Effect. Based on the limited feedback we received about the parallel circuits demonstration from HoloPhysics, it was excluded from the update. This brought our total number of demonstrations to six for these studies: Volume, Coefficient of Restitution, Ramp Kinematics, Electric Fields, Magnetic Fields from a Dipole, and the Doppler Effect.



Volume

Volume is the quantity of three-dimensional space enclosed by a closed surface, for example, the space that a substance (solid, liquid, gas, or plasma) or shape occupies or contains. Volume is often quantified numerically using the SI derived unit, the cubic metre. The volume of a container is generally understood to be the capacity of the container, i. e. the amount of fluid (gas or liquid) that the container could hold, rather than the amount of space the container itself displaces.

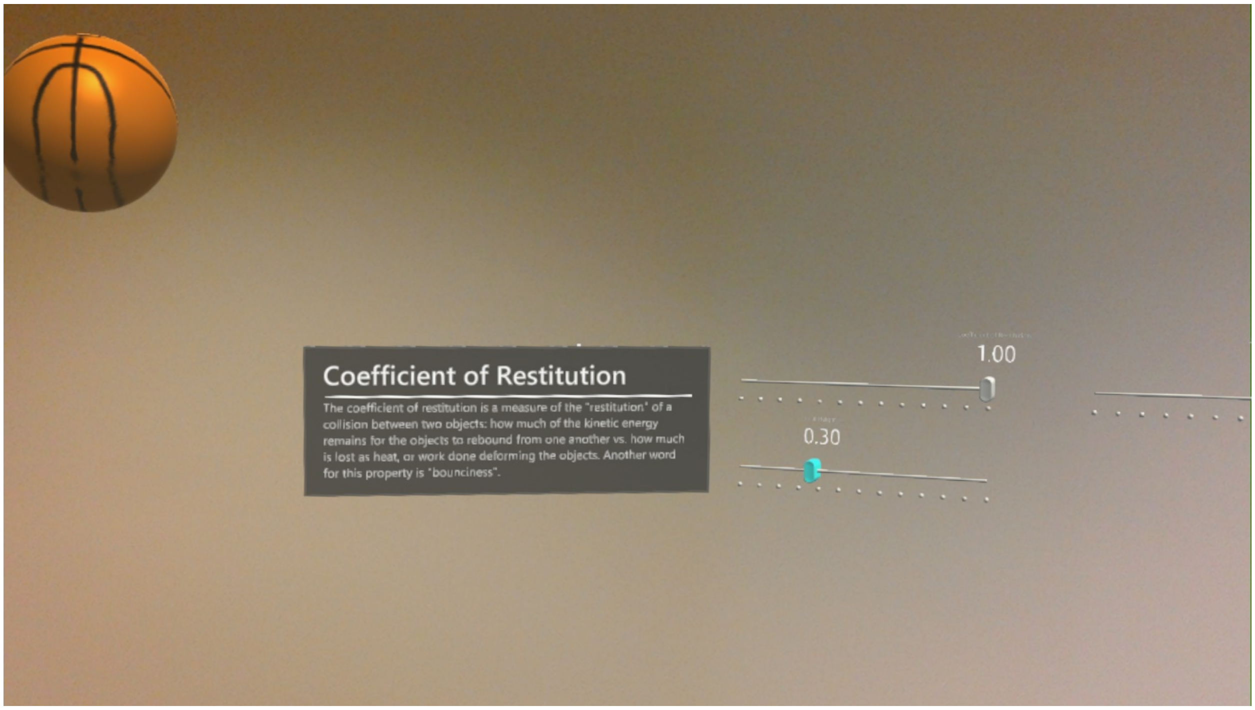
In this example, we demonstrate the change in volume of a cylinder:

$$V = \pi r^2 h$$

Figure 4.1: AR headset presenting the volume demo, illustrating the updated data presentation and a simple pair of sliders.

Volume

The user is presented with a panel describing the concept of geometric volume and the equation for the volume of a cylinder, as seen in Figure 4.1. A cylinder is presented in the scene which can be moved and rotated by the user using one handed or two-handed gestures. Two sliders are also presented to the user, one for height and one for the radius. The user can use these sliders to change the volume of the cylinder. The volume of the cylinder is presented in the scene. This concept serves as a pseudo-tutorial and simple illustration of the difference between quadratic and linear relationships of variables. It features low environmental integration along all metrics, as the only component being interacted with is a virtual ball via tap-and-drag.



Coefficient of Restitution

The coefficient of restitution is a measure of the "restitution" of a collision between two objects: how much of the kinetic energy remains for the objects to rebound from one another vs. how much is lost as heat, or work done deforming the objects. Another word for this property is "bounciness".

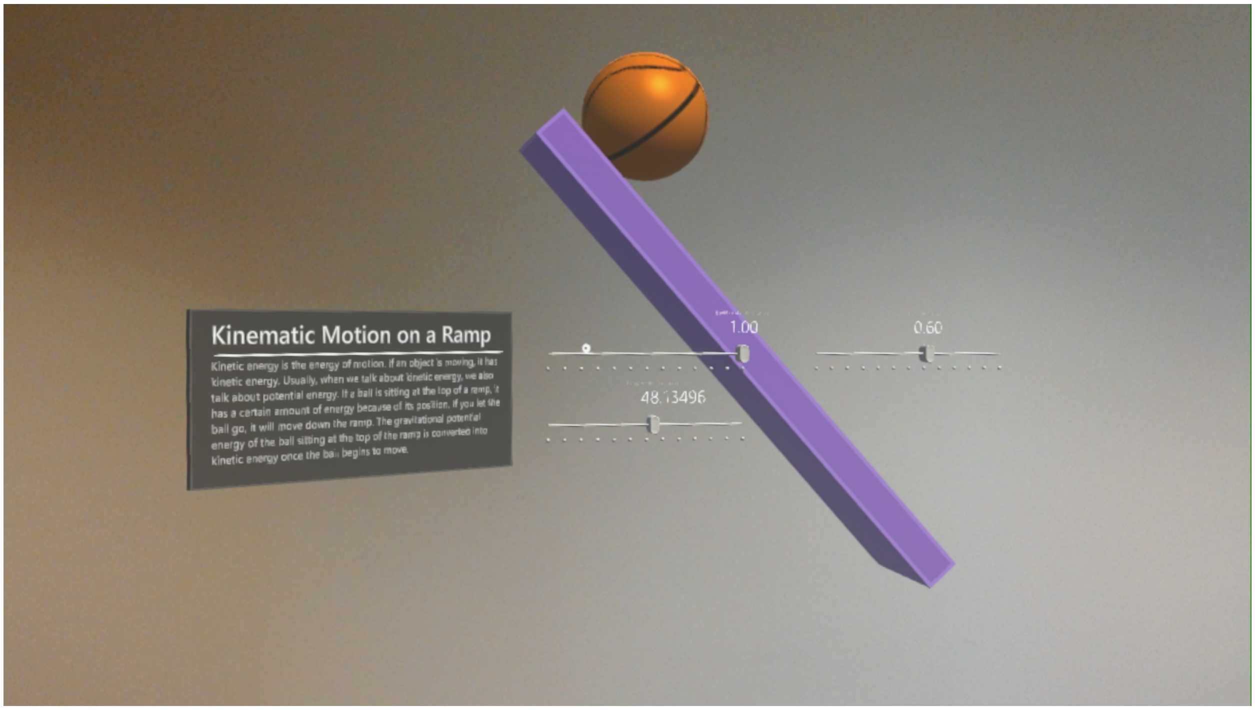
Figure 4.2: AR headset presenting the bounce demo, which has an updated visualization.

Coefficient of Restitution

As in the HoloPhysics prototype, PhyAR contains a demo describing the coefficient of restitution or bounciness of an object. A 3D text panel describing the concept is presented just to the side of the direction the user was facing on application start. A ball is present in the scene which interacts with the spatial mesh provided by the Hololens system. This ball can be picked up and moved around using the pinch gesture which is natively supported by the Hololens. Just to the right of forward are three 3D sliders for manipulating the physical parameters of the ball: dynamic friction, coefficient of restitution, and initial height. If the user manipulates the initial height slider, the ball returns to a position approximately one meter off the ground. As bounciness gets closer to 0, the ball will no longer bounce off the mesh. When bounciness is 1, the ball's collisions with the spatial mesh are truly elastic and the ball will bounce all around the room. We wanted to illustrate a greater degree of environmental integration with this concept, so we have a virtual object interacting with the physical geometry of the room. This demonstration is presented in Figure 4.2.

Ramp Kinematics

Similar to the coefficient of restitution demo, we wanted to provide an example of environmental integration, but this time, we present users with a virtual ramp, meaning the virtual ball interacts with both physical objects and virtual geometry. The users are presented with three sliders but the slider for controlling the initial height of the simulation is replaced with a slider for controlling the angle of the ramp. As the ramp angle is increased, the ball will react more dramatically with the environment. Ball placement is reset when the angle is adjusted. This demo also contains updated user interface (UI) from the HoloPhysics prototype, as seen in Figure 4.3.



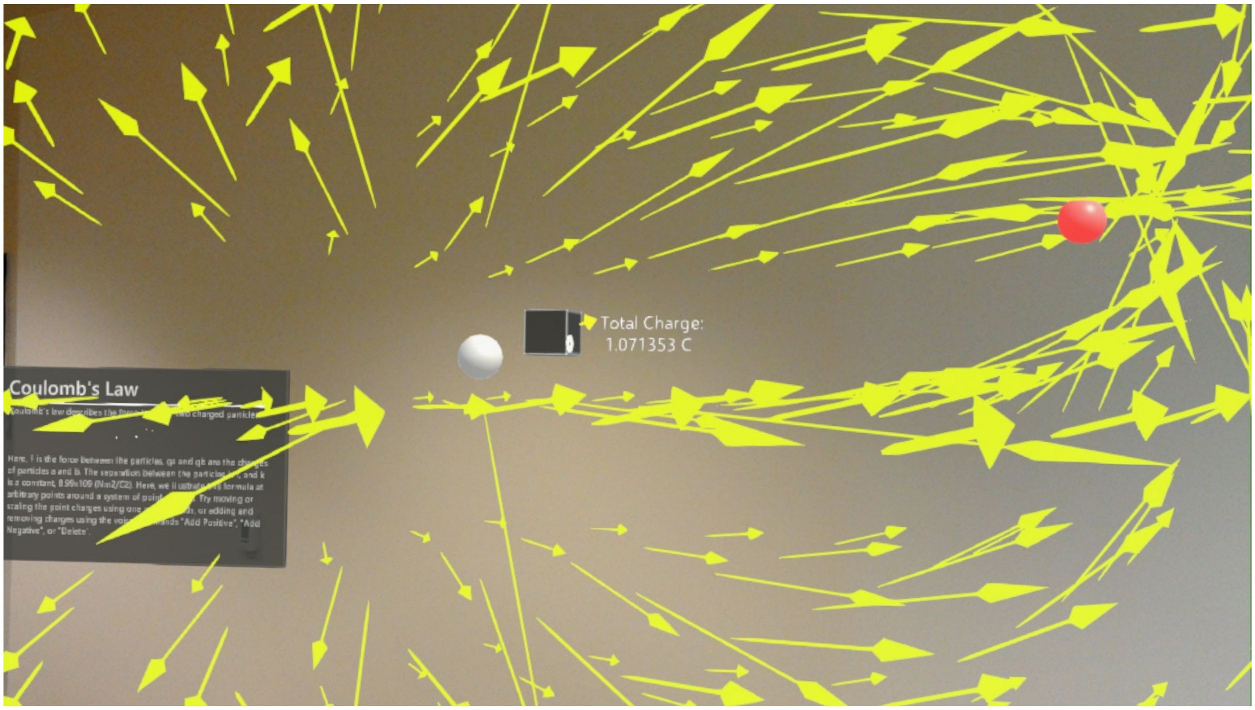
Kinematic Motion on a Ramp

Kinetic energy is the energy of motion. If an object is moving, it has kinetic energy. Usually, when we talk about kinetic energy, we also talk about potential energy. If a ball is sitting at the top of a ramp, it has a certain amount of energy because of its position. If you let the ball go, it will move down the ramp. The gravitational potential energy of the ball sitting at the top of the ramp is converted into kinetic energy once the ball begins to move.

Figure 4.3: AR headset presenting the Ramp demo, which has an updated visualization.

Electric Fields

As in HoloPhysics, a 3D grid of vectors is presented to the user. The UI has been updated to be more easily readable and voice commands are clearly defined. The user can add and remove positive and negative charges and move and scale the strength of charges freely. The vector field updates in real time according to Coulomb's Law. This updated demonstration is presented in Figure 4.4.



Coulomb's Law

Coulomb's law describes the force [illegible] two charged particles.

Here, F is the force between the particles, qa and qb are the charges of particles a and b. The separation between the particles [illegible], and k is a constant, 8.99x109 (Nm2/C2). Here, we illustrate [illegible] formula at arbitrary points around a system of point [illegible]. Try moving or scaling the point charges using one [illegible], or adding and removing charges using the voice [illegible] "Add Positive", "Add Negative", or "Delete".

Figure 4.4: AR headset presenting the Electric Field demo, which has an updated visualization.

Magnetic Field from a Dipole

A 3D grid of vectors is presented to the user, along with a fixed bar magnet and a magnetometer. The user can move, rotate, and scale the magnet in 3D space and observe the change in magnetic force at each point. The vector field visualization updates as the magnet is moved according to the equation for magnetic force at a point outside of a fixed dipole magnet. An example of this demonstration can be seen in Figure 4.5.

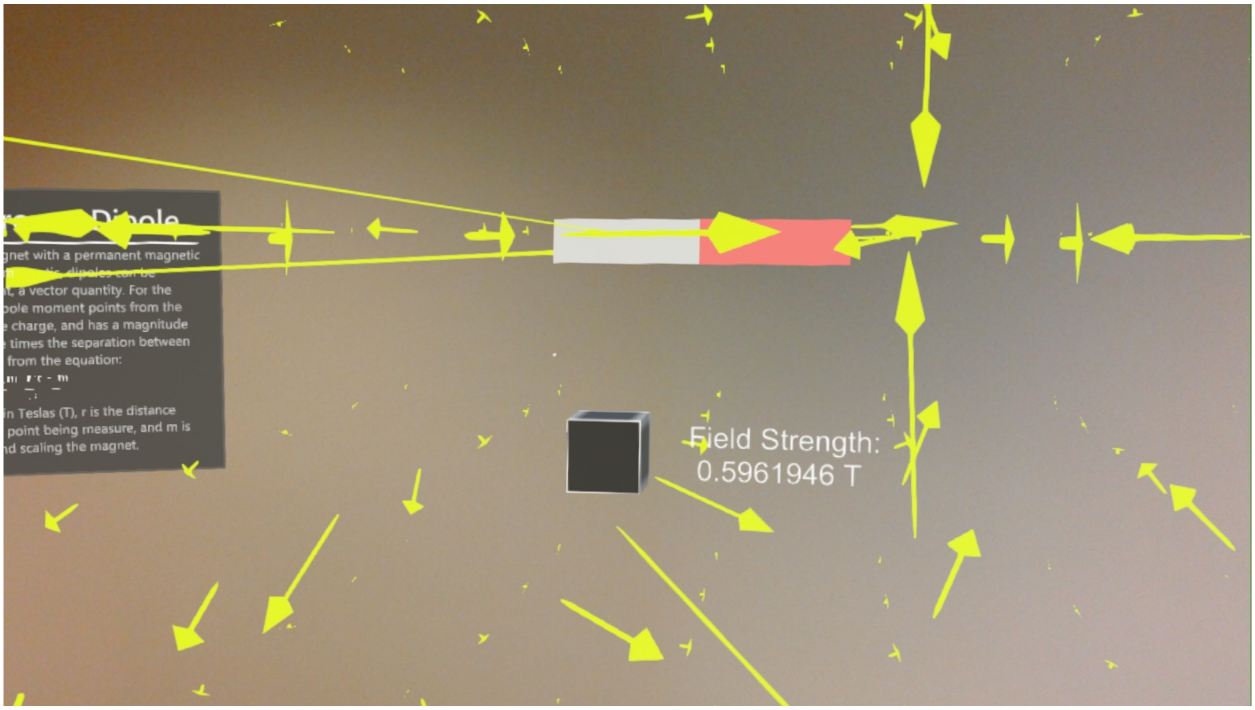


Figure 4.5: AR capture presenting the magnetic field from a dipole fixed magnet. Note that the vector field represents to point tangential to the traditional magnetic field visualization with lines at each point.

Doppler Effect

The user is presented with a text panel describing the mathematical basis for the Doppler effect and an explanation of how to use the application. In the scene are receivers and emitters, with the emissions being visible as sphere outlines from the center of the emitter. The emitter allows for control of the frequency of emission. Both objects can be moved by the user. When an emission reaches one of the receivers, a tap sound is played. As the objects move closer and further apart,

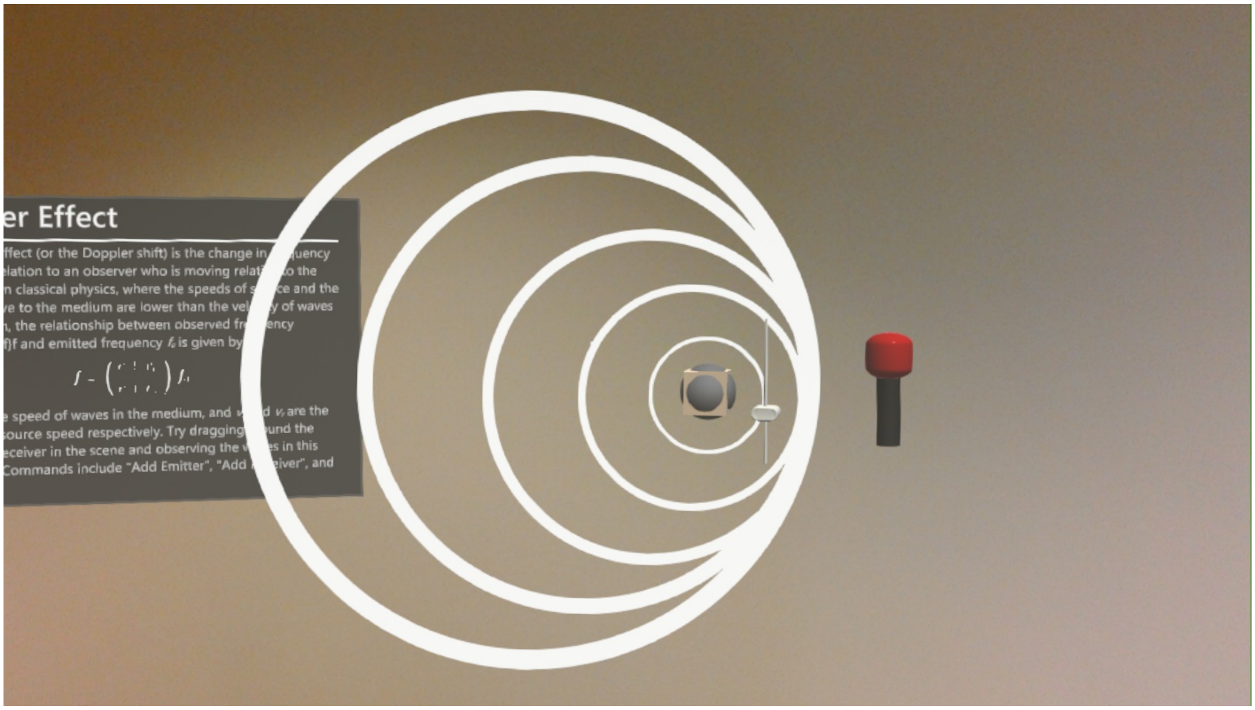


Figure 4.6: AR capture presenting the Doppler Effect in motion.

the perceived frequency of the taps changes in accordance to the Doppler Effect. An example of this demonstration can be seen in Figure 4.6.

Focus Group

To confirm that PhyAR would work with students, we organized an hour-long focus group to collect preliminary feedback about certain features. We recruited a group of seven students between the ages of 19 and 21 years. The students had all taken an introductory physics course at the university and had some degree of experience with virtual reality headsets, but not augmented reality. The group was presented with each of the six demo scenes either by demonstration from the proctor or by having the headset placed on them to experience them firsthand. Remaining members of the group could see what the active user was doing via a remote display. Feedback included that the content of the application was easy to understand, and that the idea of using AR to learn a subject was possible. Students also felt that it would be useful to collaborate with a group in a lab setting and that an augmented lecture would help to illustrate difficult content like dynamics, certain types of collisions, and gears. Some negative comments included that the application was somewhat lacking in visuals. Based on these comments, we iterated our design and updated the visuals to be more appealing. An example of this was changing out flat panel canvas assets for 3D text and sliders which were easier to read and interact with. Additional explanation text was added to the demonstrations to make it clearer for first time users about the capabilities of different scene elements.

Qualitative Study

An exploratory qualitative study was conducted to gather feedback from students on the updated prototypes and to determine where they would like to see it used in their courses. A total of 15 participants (13 male, 2 female) were recruited from the student body at the University of Central Florida. Participants were required to have 20/20 corrected vision and be able-bodied. Ages ranged from 21 to 31, with median age being 21. Each participant was asked a set of background questions about their experience with AR, VR, and their physics background. Ten of the fifteen had VR experience. Seven had AR experience of some sort. All participants were enrolled in STEM majors and were required to take two physics courses to complete their degree program: Physics I and Physics II. Twelve participants had taken or were taking the first of the two physics courses, which covers classical mechanics, waves, and thermodynamics. Nine had taken the second course, which covers electromagnetism, optics, and radioactivity, among other topics. A more thorough view of the demographic information collected is presented in Table 4.1.

Table 4.1: Demographic data of university students recruited for PhyAR study.[a] Note that blank spaces refer to courses that have not been taken by the participant.

Participant	Age	Gender	Calculus Req'd	Physics 1 Hard	Physics 2 Hard	Used VR?	Used AR?
P1	22	M	Yes			Yes	No
P2	28	M	Yes	Neutral	Neutral	No	No
P3	21	M	Yes	Somewhat Hard		No	No
P4	18	M	Yes	Hard	Hard	Yes	No
P5	21	M	Yes	Neutral	Somewhat Hard	No	Yes
P6	20	M	Yes	*Enrolled*		Yes	No
P7	20	M	Yes	*Enrolled*		Yes	Yes
P8	23	M	Yes	Easy	Neutral	No	No
P9	26	F	Yes	Somewhat Hard	Somewhat Hard	Yes	Yes
P10	18	F	Yes			No	Yes
P11	31	M	Yes	Somewhat Hard		Yes	Yes
P12	22	M	Yes	Neutral		Yes	Yes
P13	18	M	Yes			Yes	Yes
P14	20	M	Yes	Hard	Hard	Yes	No
P15	24	M	Yes	Somewhat Easy	Somewhat Easy	No	No

[a] Note that "hard" is used in place of "difficult" as on the collected demographics survey for visualization purposes.

After gathering demographics information, participants were presented with the Hololens headset and its features. The pinch gesture was described in detail to ensure interaction was not a problem. Participants were then presented with each of the six concepts with the guidance of a proctor. They were free to explore each concept until they were satisfied that they had experienced all the features within each scene. The study proctor noted any problems that were encountered by the participant. After seeing the six concepts, the participant was free to revisit any of the prior scenes; otherwise, they were asked to complete a post-study questionnaire comprised of the set of 5-point Likert scale questions listed in Table 4.2, a UMUX-Lite usability test [49] which was coded into Q1 and Q11 from the Likert scale questions, and a set of free response questions about possible use cases and preferences listed in Table 4.3. The study took approximately 30 minutes to complete and participants were compensated $5 for their time.

Table 4.2: Post-study Likert scale questions presented to the participants. Note that Q1 and Q11 combine to make up the UMUX-Lite usability questionnaire.

	Post-questionnaire Likert Questions
Q1	This AR Application is easy to use.
Q2	The content of the AR application was easy to understand.
Q3	I learned more from the AR application's presentation of information than from my lab sessions.
Q4	I learned more from the AR application's presentation of information than from my lectures.
Q5	The application was more instructive than a textbook.
Q6	The experience of using an AR headset made me want to continue using the application
Q7	I found the AR application exciting.
Q8	I found the AR application motivating.
Q9	I found the AR application interesting.
Q10	I would be able to thoroughly learn a subject from a more complete application.
Q11	This AR application's capabilities meet my requirements.
Q12	A lecture presented by a teacher using a similar headset and presenting a live video feed would be beneficial to my understanding of a new concept.
Q13	Collaborating with other students in a group lab while using AR headsets would be beneficial.

Table 4.3: The set of free response questions asked of the participants.

	Free Response Questions
FR1	Describe what you like about the AR physics application.
FR2	Describe what you dislike about the AR physics application.
FR3	In what settings would you want to use this type of application?
FR4	In what way(s) do you believe this type of application could be used in a physics class?
FR5	If you had a choice between a physical lab and an AR experiment, which would you prefer? Why?
FR6	In what way(s) could the application be improved.

Study Results

Here we detail the results of the user study. Overall, users responded positively to most aspects of the application itself but found shortcomings with the hardware.

Structured Responses

A graph of the Likert scale questionnaire responses from the survey is presented in Figure 4.7. Overall, participants found the system to be easy to understand ($M = 4.60, SD = .51$), exciting ($M = 4.60, SD = .51$), motivating ($M = 4.27, SD = .80$), and interesting ($M = 4.87, SD = .35$). These results were expected as there is typically positive feedback from participants when exposed to a new application. To a lesser extent, users found that they could learn more than a lab session($M = 3.8, SD = .87$), formal lecture ($M = 3.53, SD = 0.91$), or textbook ($M = 3.86, SD = .74$) using PhyAR or a similar, fully-featured application. Participants wanted to continue using the AR application after the study ($M = 4.27, SD = 1.10$) and felt that they could learn more from a more complete application ($M = 4.46, SD = .64$). Students also responded positively to the ideas of augmented lectures using a remote display to see an augmented lecture ($M = 4.47, SD = .83$) and sharing a space with other students in an augmented physics lab ($M = 4.27, SD = 1.03$).

To transform our data for use in the UMUX-Lite test, we summarized and normalized the responses to question Q1 (Easy to use, ($M = 3.93, SD = 1.16$)) and Q11 (Meets requirements ($M = 3.93, SD = 1.16$)) to be on a scale from 0 to 100. We then applied a linear regression to this value to properly align it with the SUS scale [49]. The results of the UMUX-Lite test show that the application is sufficiently usable for the task at hand ($M = 72.2, SD = 13.9$) due to the score exceeding the threshold value of 50. Note that issues related to usability were frequently mentioned

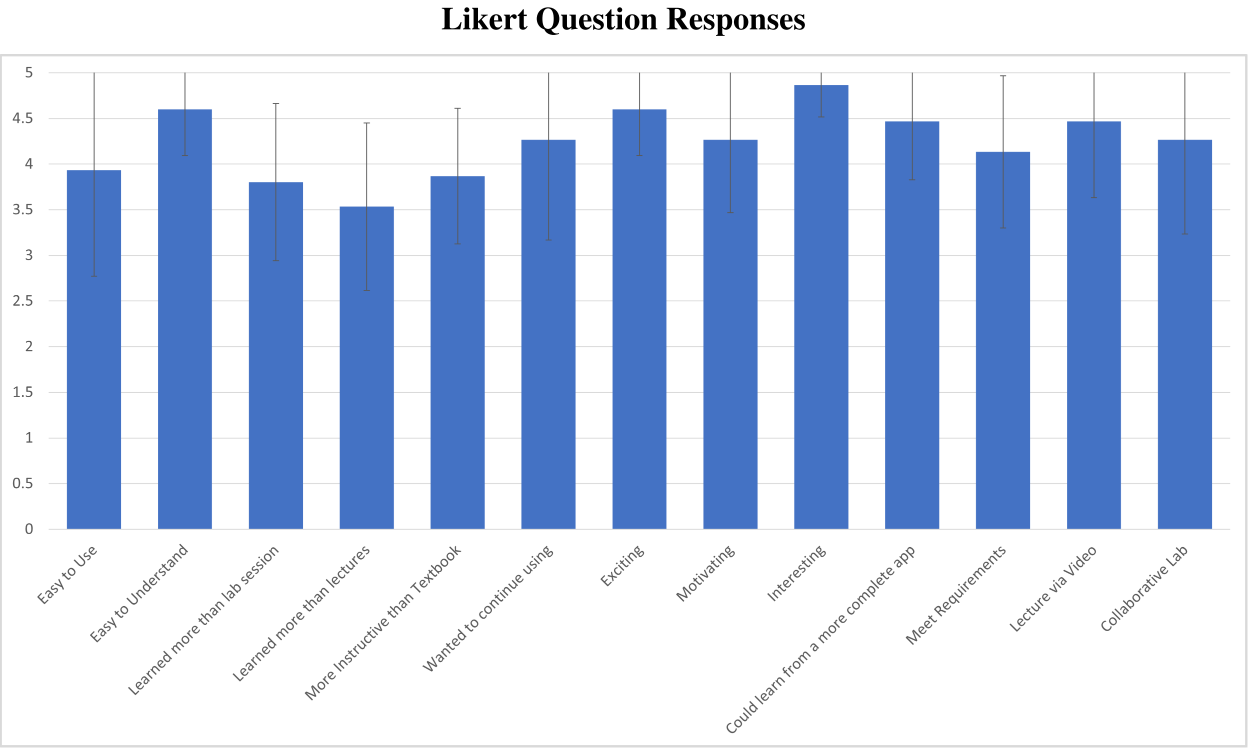


Figure 4.7: Mean responses to Likert scale questions from the PhyAR study.

by participants and will be detailed in the next section.

Free Responses

For each of the free response questions, a set of codes were generated, and the answers were then coded to one or more of the resultant categories. These codes and their frequencies can be seen in Table 4.4. A few patterns occurred in the free response questions. Sixty percent of participants reported that they found the dynamic visualizations to be one feature they liked. Similarly, 60 percent of participants liked that the application was interactive in some way. One participant stated, ”I liked the presentation of information and buttons; the system was interactive and gave free rein over the area to explore and play around.”

Most of the dislikes reported were the result of device specific issues relating to limited field of view causing objects to not be visible in the room. Three of the fifteen students had specific problems with the hardware being uncomfortable. Nearly half of participants had problems with built-in controls of the Hololens, specifically with the pinch gesture needed to select the objects in the scene and two-handed pinching to manipulate objects. The proctors ensured that the participants were able to appropriately execute the gestures. One participant summarized these issues well: ”It gave me a slight headache after using it for around 15-30 minutes. It seemed simple to control but it did not always detect my attempts to try and pick up objects or move the sliders.” It can be assumed that future devices will enable better native interaction and be designed with extended use in mind, so these would no longer be issues.

Feedback from participants about preferred concepts for presentation in AR covered the full spectrum of a physics course. Students saw possible use for exploratory study on their own time, in collaborative laboratories with shared spaces, and with instructors presenting augmented lectures. Seventy-three percent of students echoed the use of augmented lectures to assist in learning some newer concepts, with one participant specifying that it could be ”...used for labs and lectures, especially hard concepts that are hard to explain on a whiteboard or slide.” Nine participants felt that there was some possibility for replacing a number of formal labs with an AR element, possibly as a way to get a sense for a concept before carrying out a physical lab.

All participants provided some ideas for improving the application. Opinions were divided on how best to improve, though a majority focused on visual and interaction elements. Participants wanted to see a more thorough application that covered more details of each physics concept, such as visualizations of vectors in the kinematics demos. Participants also wanted more natural interaction to be supported in the form of hand tracking and additional voice over explanations of the concepts.

Table 4.4: List of the codes and frequencies for each of the six free response questions. Frequencies are out of the 15 participants.

Question	Code	Frequency
FR1	View Perspective/Immersion	3
	Dynamic Visualizations	9
	Interaction	9
	Easy to Understand	2
FR2	Limited Field of View	5
	Uncomfortable Device	3
	Hard to Control/Unresponsive Gestures	7
	Limited Features	1
FR3	Individual Study	10
	Collaborative Projects	9
	Instructor Demonstration	11
FR4	Augmented Lecture/Supplementation	11
	Reinforcement	4
	Difficult to Visualize	4
FR5	AR	9
	Physical	3
	No Preference	3
FR6	Visual	6
	Hardware	5
	Interaction	6
	Conceptual	1

Discussion

The results of the qualitative student study support and echo the ideas that were presented by the educators. Examples of this include augmented lectures and working in collaborative groups on shared experiences, as referenced in the Discussion section in the previous chapter. We can infer from the results that there is a niche in the classroom that can be satisfied by AR, be it in labs, lectures, or for distance learners. Both students and educators expressed positive feedback, specifically in motivation-aligned measures, and were encouraged by what was presented to them.

This positive experience was in spite of any presentation shortcomings or interaction problems that users may have experienced. The imperfect nature of the application is no different from the imperfect nature of physical labs. The nature of the imperfections, or mistakes, that can occur vary between AR and physical labs. In a physical lab, students apply the incorrect formula or execute the lab procedures inaccurately. Both mistakes reflect a lack of understanding that could be alleviated by additional guidance that an AR application could provide.

It is worth noting that the version of PhyAR presented to participants did not include any physical world interaction outside of spatial mesh collisions in the two ball-based demos. This is one of the major shortcomings of the study that the students experienced as it primarily leverages the AR display but not the environment around the user outside of the basic geometry of the room. Without physical interactions, the same experience could be presented to students in VR with a virtual environment. This, though, would be detrimental to in-person collaborative experiences, which benefit greatly from the ability to see the real world while looking at the virtual objects to allow communication with teammates or peers. While we did not receive much feedback from students emphasizing any AR-exclusive properties, we still point towards the feedback which we received from educators which encouraged the use of additional visualizations overlayed on real objects during studies, as in the parallel circuits in the first iteration of our prototype, HoloPhysics. This is something that cannot be replicated with traditional opaque VR setups. Similarly, the ability to present a similar experience in VR without physical world interaction does not invalidate the utility of AR; it speaks to the flexibility that AR enables. Conversely, there is nothing that VR experience can present that can not present similarly in an AR experience, except for immersion in a separate space.

CHAPTER 5: PhyAR 2: EXPLORING THE BENEFITS OF AR FOR ELECTROMAGNETISM LESSONS

Feedback collected during the first two studies provided a clearer idea for what the prospective user groups would like to see. With this feedback, it is beneficial to look back at the original research problem to determine how best to answer it. We have to this point collected some design requirements and student feedback about fairly shallow demo applications. The original goal with this research project is to determine if augmented reality physics applications with a significant degree of physical world integration will improve student understanding, retention, and enjoyment in physics courses.

Based solely on the first two studies, the only context from the real world that was used was geometric information from the environment at most, with no real ”integration” with the flow of the application. Of the scenarios implemented in these earlier prototypes, only the light switch parallel circuit demonstration truly illustrates what AR is uniquely capable of doing. Aligning and interacting with real objects while presenting virtual information and objects that change in real time is a better indicator of an AR experience. Additionally, there are extensions that derived from the HoloPhysics and PhyAR studies which would be beneficial to addressing this question. Let’s first consider possible improvements to the existing PhyAR application which would need to be implemented to better illustrate some use cases for AR in the physics classroom which have previously been discussed:

- **Improve the PhyAR prototype based on student feedback:** Students and teachers who participated in the studies brought up the idea of working with a group of students on subjects that more closely aligned with traditional physics labs. Students also wanted PhyAR to be easier to interact with, which means an alternative must be provided to pinch gesture in the

Hololens.

- **Presentation of force vectors on real objects:** One piece of feedback which was collected from educators and feedback from researchers in the field was the idea that most of the examples presented in both prototypes do not leverage AR capabilities enough. All the developed examples could easily be carried out in a fully virtual environment without any significant changes. To better utilize AR capabilities, it would be beneficial to add force diagrams to real and virtual items for lab style studies.
- **Make real objects influence the virtual overlays being presented:** None of the demonstrations which have been studied have contained any physical objects for students to interact with. It could be beneficial for students to have tangible objects to manipulate to give them better methods of interaction than the Hololens typically allows. Similarly, illustrating the change in magnetic and electrical fields near real electrical household items would better illustrate the pervasiveness of physics to students.
- **Presenting Augmented Lectures using AR:** Educators wanted the ability to use an AR device to present demonstrations during their lectures that students can watch via a live-video feed. This would keep hardware requirements for a department low, thereby keeping costs down. The augmented elements would need to feature clearly legible content for someone viewing a video feed.

Each of these areas is of sufficient breadth to warrant significant exploration. All required significant further work into the PhyAR prototype that has been developed for the previously completed user studies. However, for the sake of selecting an appropriately scoped study, we disregard collaborative experiences and force vector visualization on projectile motion objects. We instead focus on two concepts in greater depth and integrate some degree of real world understanding, therefore satisfying the first and third items from the previous list. We discuss our approach designing the next version of the PhyAR application in this chapter, as well as detail a user study that was carried out to evaluate it in greater detail than the previous studies. The study we present in this chapter differs from previous chapters, as we previously had no baseline comparison and were gathering user opinions of AR's possible use in the classroom. In this study, we instead wanted to compare against another, similar method of immersive information presentation: Virtual Reality. In addition to our original two research questions, a question we wanted to answer in this study is the following: is presenting new physics concepts in AR more beneficial to learning results than VR? Based on the results we collected, we found there to be only a small benefit to presenting the information in a real world, AR experience when compared to the VR experience we presented. Participant sentiment and results are reported.

Updating PhyAR: Designing Version 2

Many students who were presented with PhyAR wanted to see more exposition added into the conceptual demonstrations presented during the second user study. Similarly, students wanted improved interaction with the objects in the scenes, such as methods ensuring that important objects are easier to locate when they move out of view when dealing with room-scale interaction. We considered all the feedback that was collected valid, though a number of the criticisms are device-centric, such as those relating to limited field of view and difficult pinch gestures. We chose to disregard any issues relating to the Hololens itself. Our first steps were to create more detailed scenes for each of the concepts which were selected for further elaboration to more thoroughly illustrate the concept and give very clear direction, so students do not need a proctor to explain how to use specific elements of a presented demonstration. From a long term perspective, this would do well to improve adoption as it would remove the need for expert guidance.

The parallel circuits demo was the start of what people would consider the most important part of the work: helping students visualize how physics is present in the world around them. When selecting how version 2 of the PhyAR application would look, we wanted to have more connections to the real world but wanted to select a method of presentation that would be more easily deployed to different areas. Initially, we wanted to leverage object recognition for a set of objects that would interact with the Unity application and be integrated into the electrical field and magnetic field demonstrations. There were severe computational limitations with the Hololens device which limited the ability for the device to easily handle object recognition and still maintain a usable visual frame rate. To alleviate this problem, we instead turned to marker based detection of objects and created a set of 3D printed objects to attach them to, as presented in Figure 5.1. When the objects are moved, a corresponding virtual object is moved within the AR application, which will have effects on AR visualizations, as presented in Figure 5.2. We discuss some implementation details relating to this in the following section.

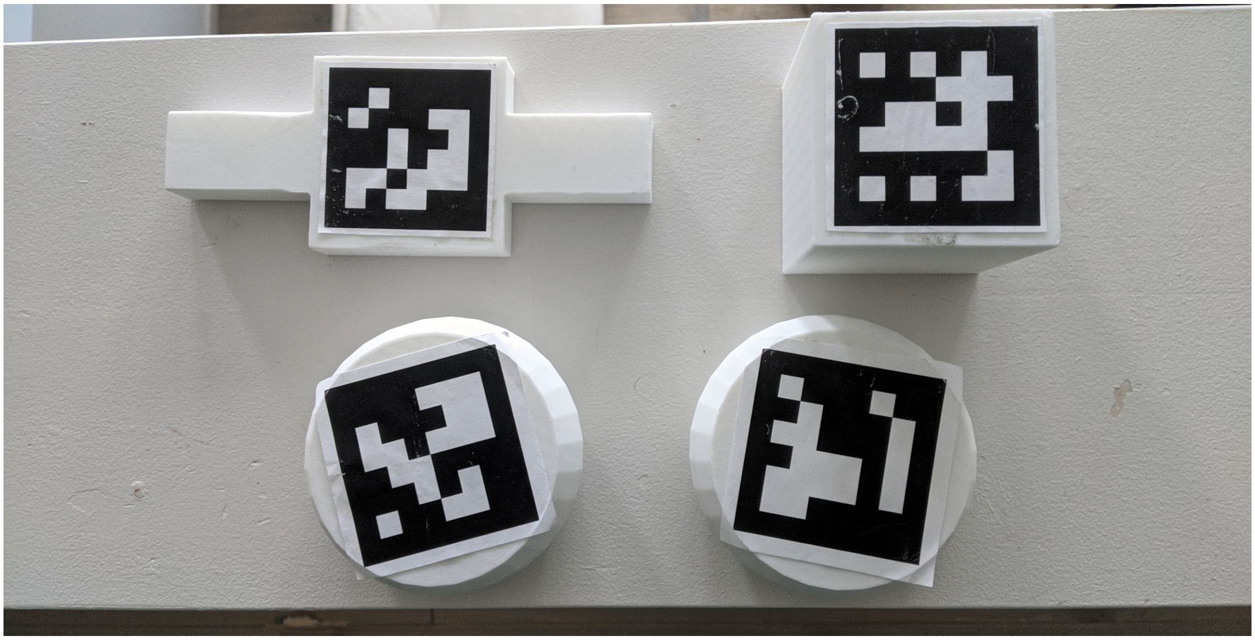


Figure 5.1: The 3D printed physical objects that are used in PhyAR2 as the shapes that tracked by the application in lieu of using pinch- and gaze- based manipulation for translation/rotation.

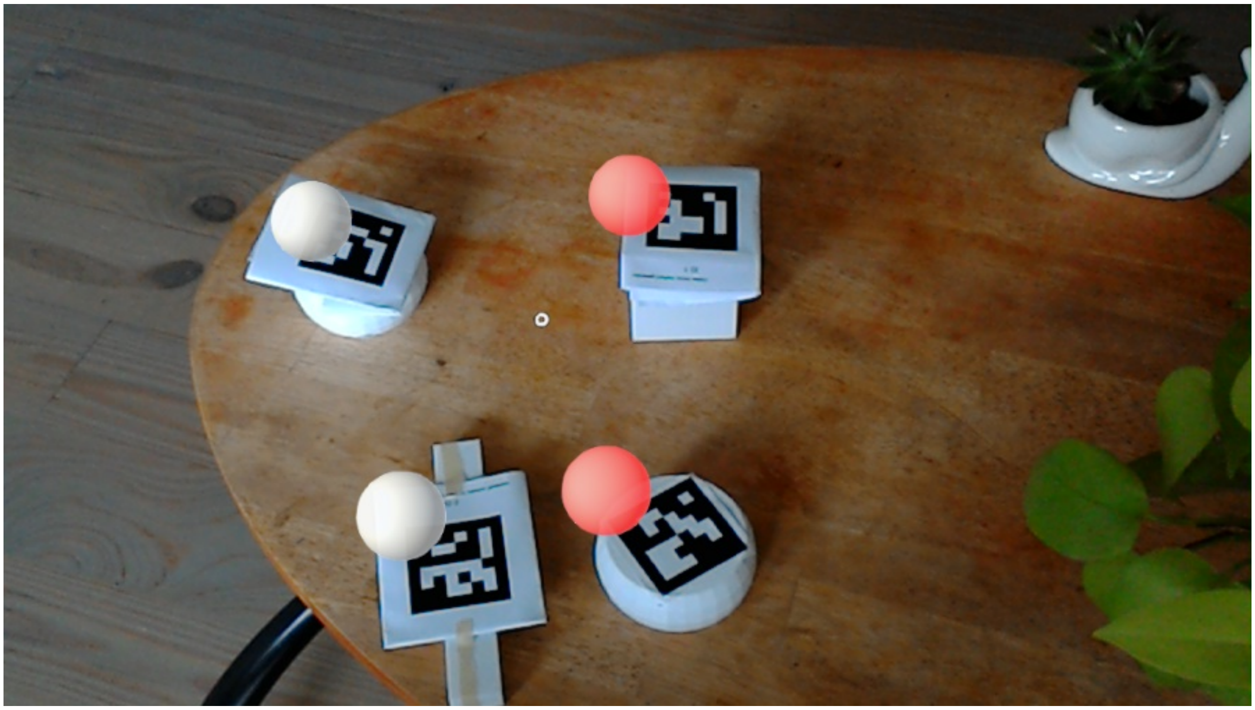


Figure 5.2: 3D printed objects with their corresponding overlay in the augmented environment. Note that the alignment is incorrect due to a calibration artifact from the Mixed Reality Capture used to generate this image.

Implementation Details

As in version 1 of PhyAR, PhyAR2 leverages the Unity3D game engine and a Hololens 1, though some changes needed to be made. The first is that we are no longer relying as heavily on the pinch and gaze based interaction that Hololens 1 required; numerous participants said that it negatively effected their experience and we would therefore like to minimize its use in PhyAR2. The second major change is that the application makes use of openCV [11] to detect markers on the tracked objects in the scene. These markers are used to track the physical objects that the participants can interact with, which causes changes to graphs and diagrams in the scene. Another change is that participants are instead being asked to proceed through longer sessions on a single topic instead of viewing different vignettes on different topics. We found that a number of the PhyAR version 1 experiences were redundant to some extent so we instead emphasize two concepts: Faraday's Law and Coulomb's law. These lessons will be explained in more detail in the section titled "Selected Concepts." We also found that it is important to present the mathematics backing up what is being presented to students in controlled environments, so real time visualizations of the important equations were added, as shown in Figure 5.3. We believed that this would assist those students who primarily learn from analytical presentation of information instead of conceptual presentations. An architecture diagram of the application is presented in Figure 5.4.

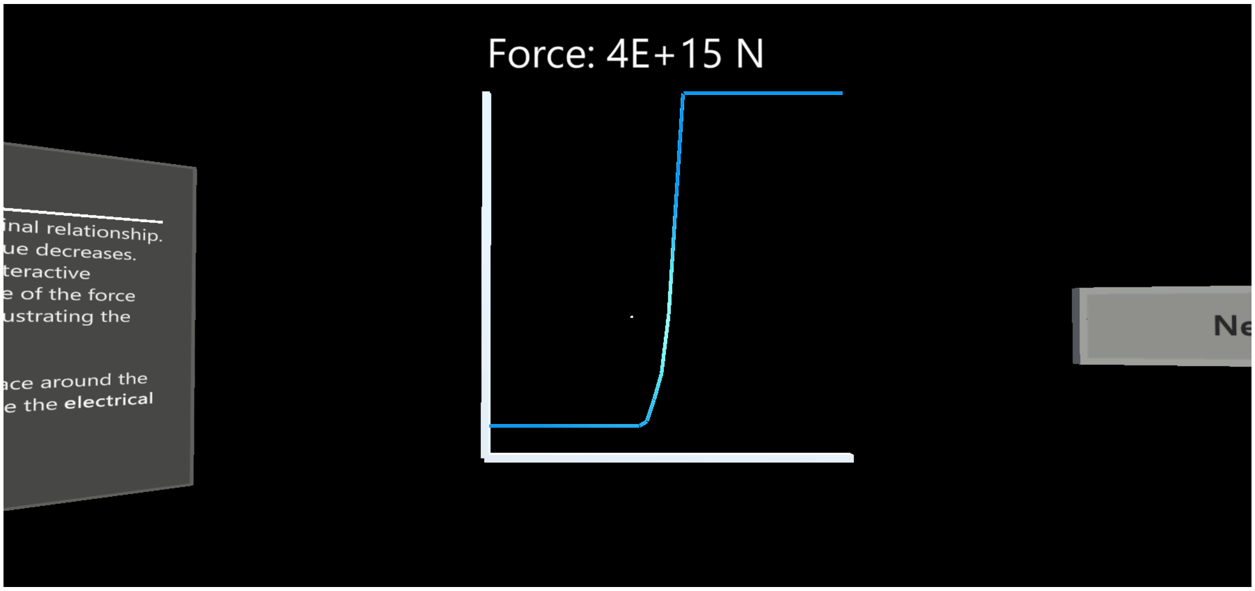


Figure 5.3: Example of the real-time graph presented in the application.

Virtual Reality Implementation

For the sake of the evaluation we designed, we also needed to generate a virtual reality version of this application. To do this, we leveraged the Mixed Reality toolkit and Unity 3D game engine to create a VR analogue of the AR application. We created a virtual environment which simulated

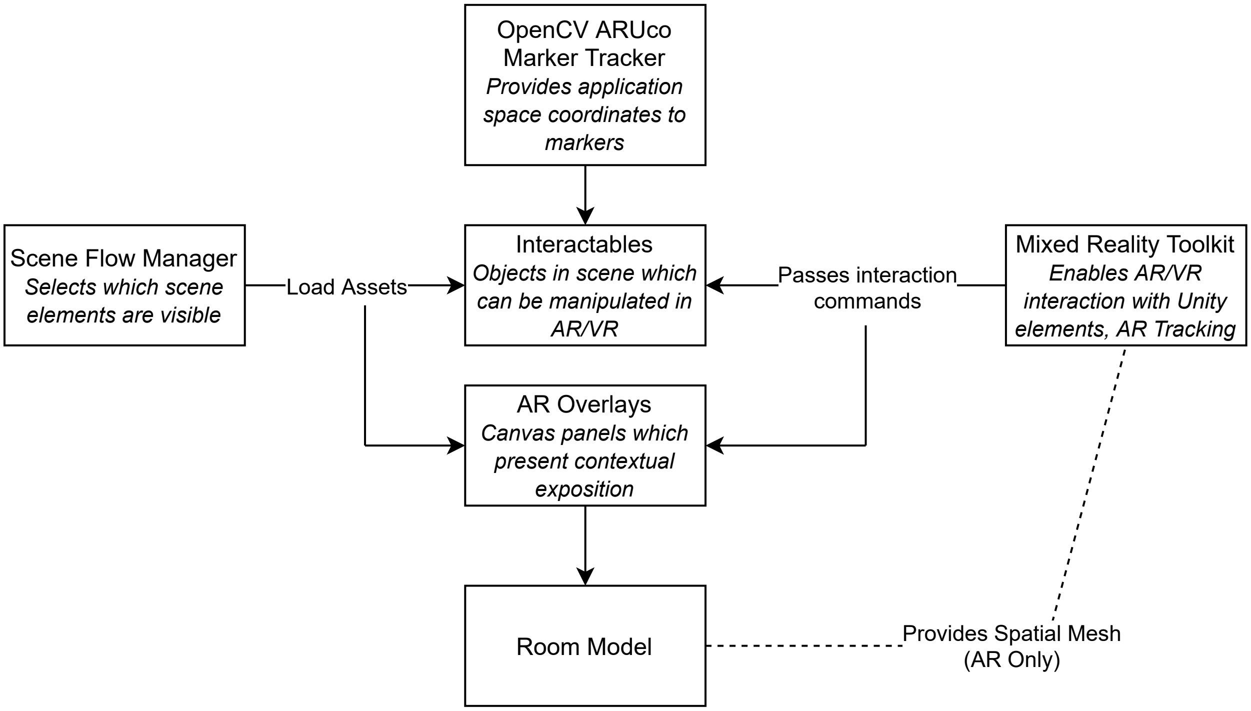


Figure 5.4: Architecture diagram of PhyAR2.

a living room with a desk and chair placed inside it. Users interact with virtual objects using controllers instead of gaze based interaction or tracked markers. In designing the application in this way, we wanted to determine if VR devices, which are often lower cost than AR devices, could provide a similar experience without using actual tangible objects. Feedback from the PhyAR version 1 research pushed this design decision. An image of the virtual environment used in this example is presented in Figure 5.5.

The headset used in this implementation is an HP Reverb, displayed in Figure 5.6. It features a 90 Hz refresh rate, 114-degree field of view, and a 2160x2160 resolution per eye. The headset features inside-out tracking, which means there are no external trackers needed to provide the simulation/application with any position and orientation data. The headset is paired with two bluetooth controllers, one for each hand. These controllers are tracked using integrated 6 degree-of-freedom trackers and optical markers which are tracked using cameras on the headset. We connected this headset to an HP Z VR Backpack PC, a portable desktop designed specifically with VR use in mind. It ran Windows 10 Pro with an Intel Core i7, 32 GB RAM, and an NVIDIA Quadro P5200 video card. During preliminary testing, we experienced 90 fps performance at all times when interacting with the PhyAR2 application.

Figure 5.5: The virtual environment presented in the VR version of the PhyAR2 application.

Selected Concepts

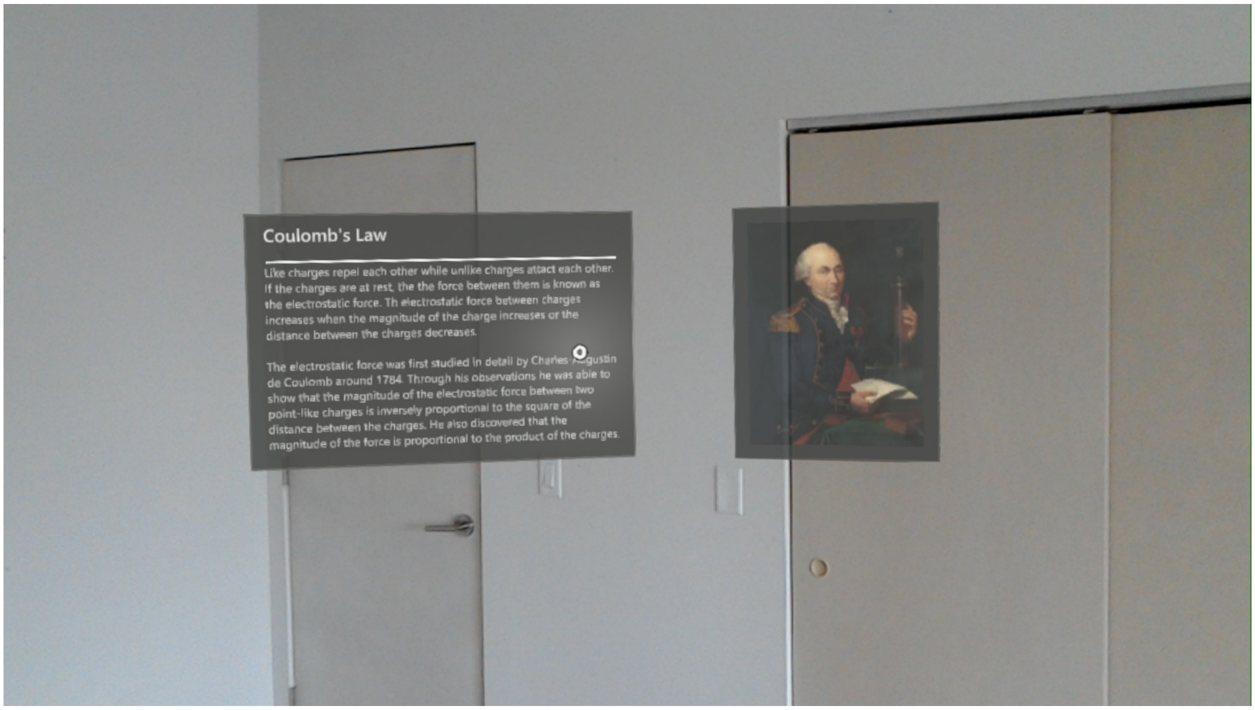
We spent a great deal of time trying to select the topics that best would benefit from some form of AR presentation. One issue that continued to arise was the complexity question: Is it easier to visualize this concept by doing something with real world objects than it is to deal with the inaccuracies of AR overlays and tracking? For concepts like projectile motion and basic forces, the answer to this question was a resounding ”yes.” Trying to track objects with even state-of-

Figure 5.6: An HP Reverb, the VR headset used for the VR condition in the PhyAR2 study.

the-art AR devices was beyond the original scope of this project and deviated greatly from the questions the study most needed to answer. Instead, we focus on concepts that are more difficult to visualize, specifically Coulomb's Law and Faraday's Law. These form some earlier lessons in electrical charges and magnetism, respectively. Both of these concepts emphasize some invisible force that requires specialized equipment to measure. Here we provide some depth about the lesson design about each of these concepts.

Coulomb's Law

PhyAR2 includes a lesson specifically about Coulomb's Law. In a departure from the previous version of the prototype, the application includes multiple pages of a specific concept instead of sandbox style presentation of vastly different concepts. The Coulomb's Law illustration includes the following pages:



Coulomb's Law

Like charges repel each other while unlike charges attact each other. If the charges are at rest, the the force between them is known as the electrostatic force. Th electrostatic force between charges increases when the magnitude of the charge increases or the distance between the charges decreases.

The electrostatic force was first studied in detail by Charles-Augustin de Coulomb around 1784. Through his observations he was able to show that the magnitude of the electrostatic force between two point-like charges is inversely proportional to the square of the distance between the charges. He also discovered that the magnitude of the force is proportional to the product of the charges.

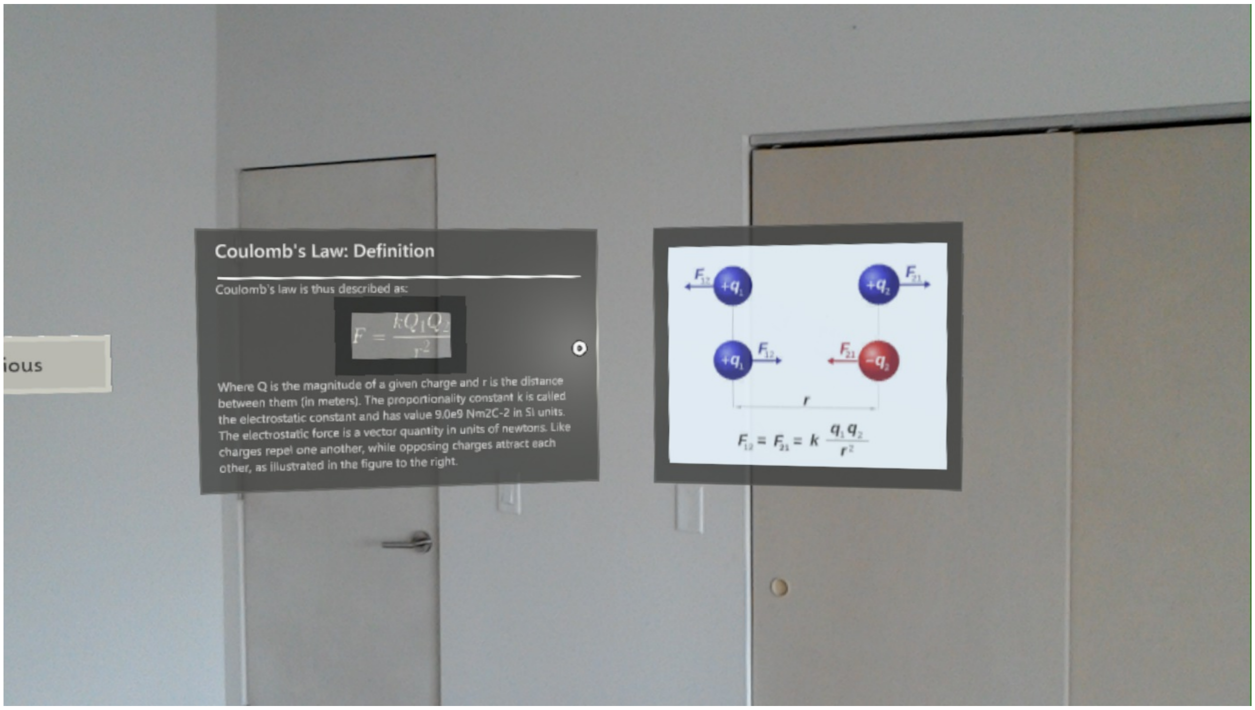
Figure 5.7: The 2D diagram presented on page 1 of the Coulomb's Law lesson in the PhyAR2 application.

Background on Coulomb's Law

On the first page, the application presented a panel to the user with some background information about Coulomb's Law. This included some of the history of the development of the equation and its foundational importance to electricity overall. The AR version of this page is presented in Figure 5.7.

Formal Definition of Coulomb's Law

A formal definition of Coulomb's Law is presented to the user in the form of an equation and a static image of what is normally presented in a textbook. The 2D figure that is presented can be



Coulomb's Law: Definition

Coulomb's law is thus described as:

$$F = \frac{kQ_1Q_2}{r^2}$$

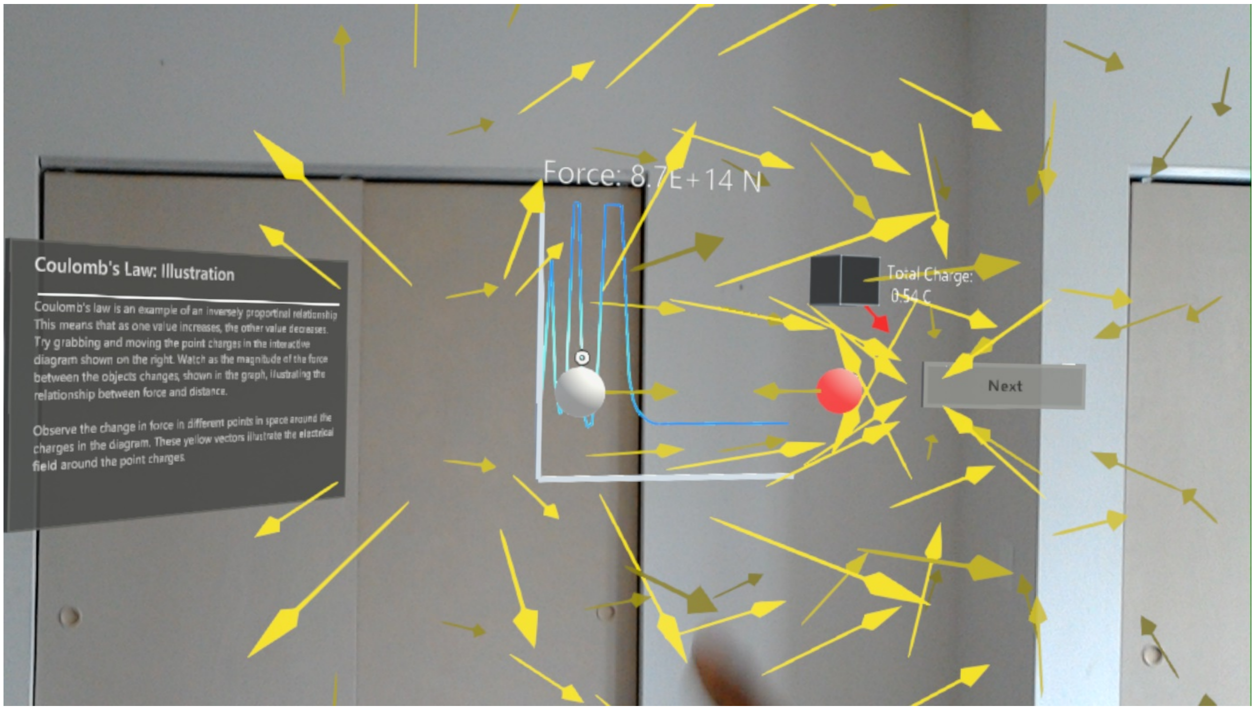
Where Q is the magnitude of a given charge and r is the distance between them (in meters). The proportionality constant k is called the electrostatic constant and has value 9.0e9 Nm2C-2 in SI units. The electrostatic force is a vector quantity in units of newtons. Like charges repel one another, while opposing charges attract each other, as illustrated in the figure to the right.

Figure 5.8: The 2D diagram presented on page 2 of the Coulomb's Law lesson in the PhyAR2 application.

seen in Figure 5.8.

Grid Demonstration of Point Charges

Page three of the Coulomb's Law lesson includes the 3D grid of vectors and interactable point charges that were present in the older Coulomb's Law visualizations from HoloPhysics and PhyAR. Users are able to move the tracked physical objects to move the point charges inside the application and observe changes in the surrounding charge of the presented point charges. The scene also includes the scope which can be used to measure the charge at different points in space, just as in the older presentations, as showed in Figure 5.9



Coulomb's Law: Illustration

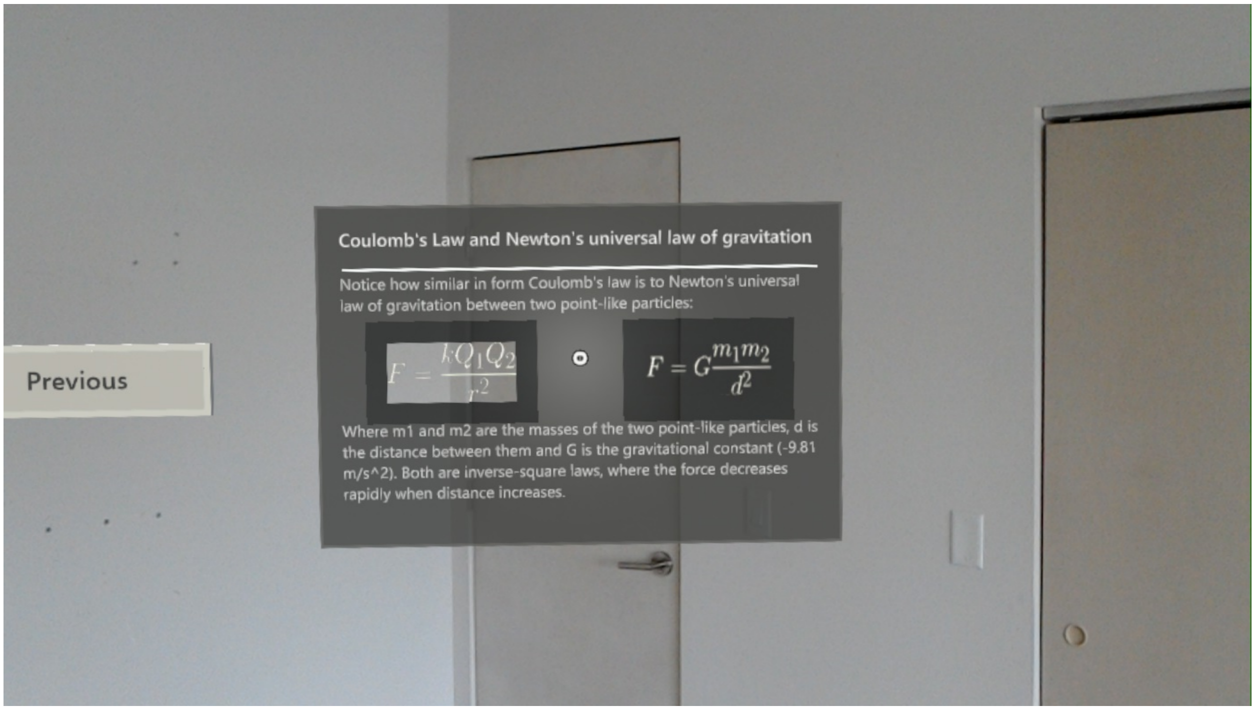
Coulomb's law is an example of an inversely proportinal relationship This means that as one value increases, the other value decreases. Try grabbing and moving the point charges in the interactive diagram shown on the right. Watch as the magnitude of the force between the objects changes, shown in the graph, illustrating the relationship between force and distance.

Observe the change in force in different points in space around the charges in the diagram. These yellow vectors illustrate the electrical field around the point charges.

Figure 5.9: The 3D diagram presented on page 3 of the Coulomb's Law lesson in the PhyAR2 application.

Comparison to Gravity

Physics is an iterative subject, with different concepts being slowly stacked on one another to ensure students are not lost along the way as the physical world around them is more thoroughly revealed to them. On page 4 of the Coulomb's Law demonstration, we present one example of how relationships between different concepts can manifest themselves, this time in the analogous relationship between gravity and electrical force between charges, as shown in Figure 5.10.



Coulomb's Law and Newton's universal law of gravitation

Notice how similar in form Coulomb's law is to Newton's universal law of gravitation between two point-like particles:

$$F = \frac{kQ_1Q_2}{r^2} \qquad F = G\frac{m_1m_2}{d^2}$$

Where m1 and m2 are the masses of the two point-like particles, d is the distance between them and G is the gravitational constant (-9.81 m/s^2). Both are inverse-square laws, where the force decreases rapidly when distance increases.

Figure 5.10: The 3D diagram presented on page 4 of the Coulomb's Law lesson in the PhyAR2 application.

Laboratory Exploration

The final page is a laboratory style exploration of Coulomb's Law, where users are presented with a graph of the force between the point charges in the scene and tracked point charges. The user is asked to explore the scene to get a better sense for the interactions between different point charges in space. The point charges can be moved using the built-in pinch and grab gesture in the Hololens, using physical objects with Fiducial markers attached to them, or using the raycast-based manipulation enabled in the VR configuration. There are a total of 4 tracked point charges which can be freely moved around the diagram.

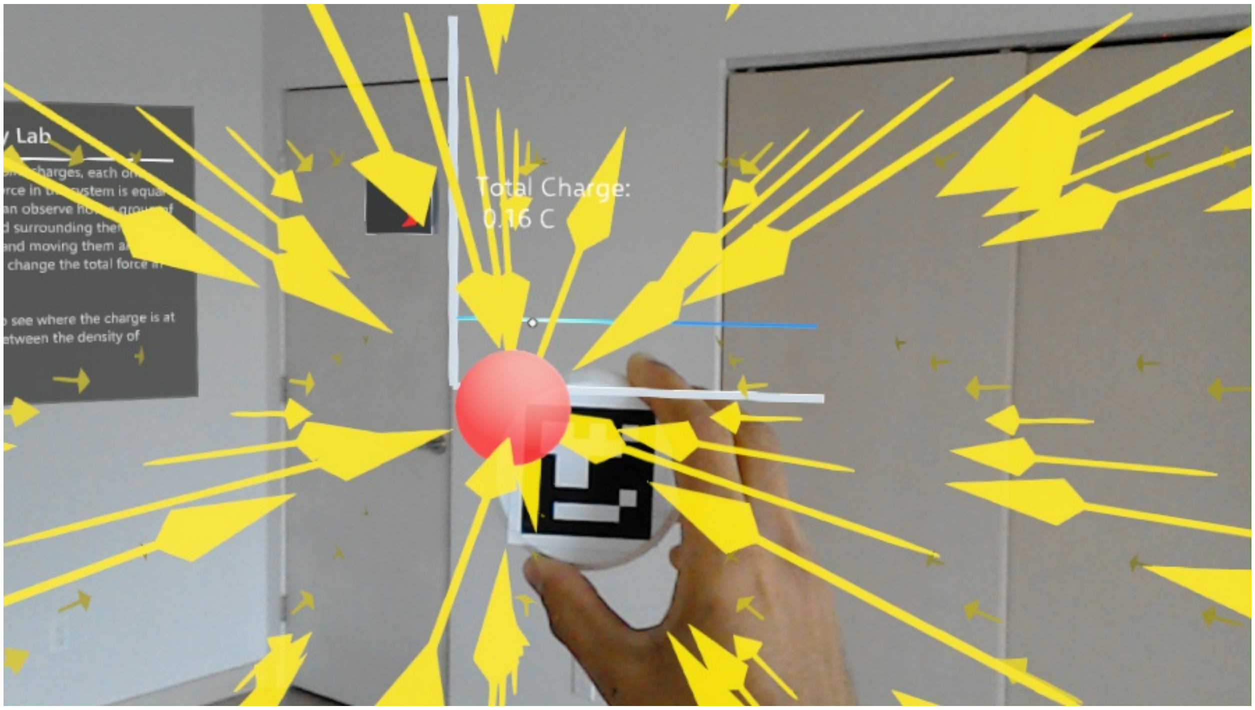


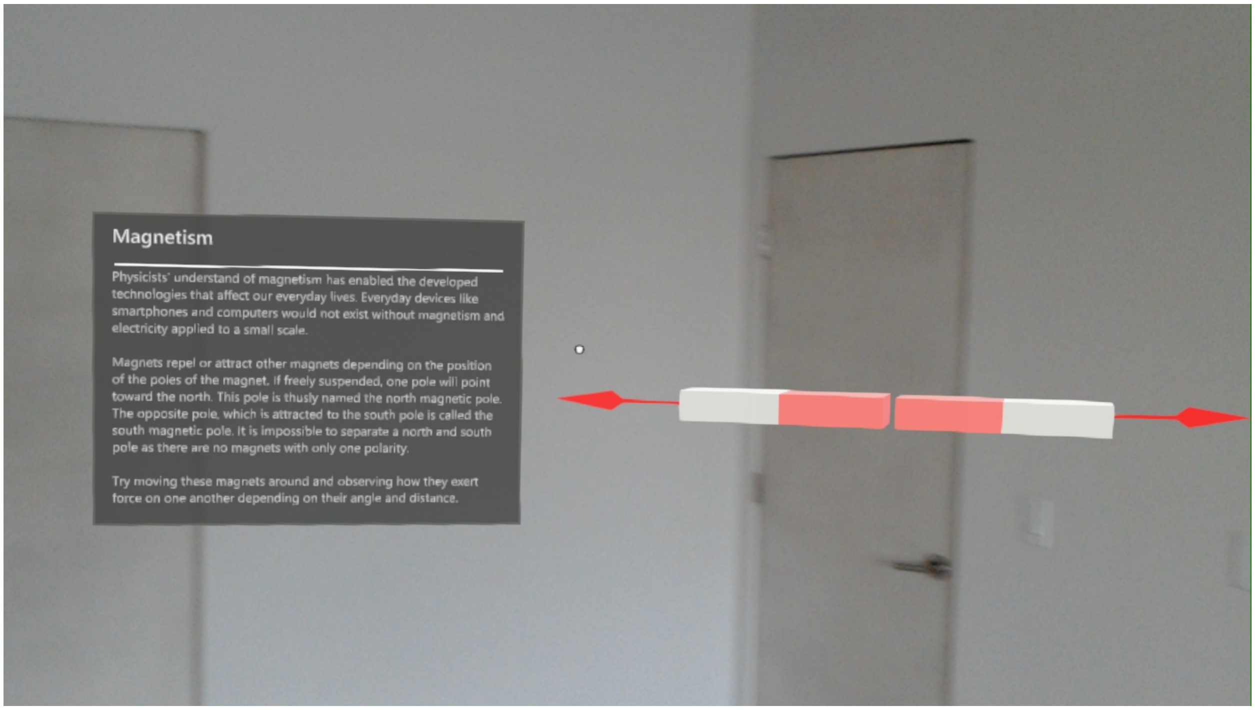
Figure 5.11: The 3D diagram presented on page 5 of the Coulomb’s Law lesson in the PhyAR2 application.

Magnetism and Faraday’s Law

PhyAR2 also includes a lesson specifically about electromagnetic induction, specifically Faraday’s Law of electromagnetic induction and magnetic fields. This concept was also briefly included in PhyAR version 1, but was not expounded upon to a great degree. In PhyAR version 2, the following content is presented in the study flow.

Background on Magnets

On the first page, the application presented a panel to the user with some background information on magnets. This includes a brief explanation of the concept of ”opposites attracting” and ”likes



Magnetism

Physicists' understand of magnetism has enabled the developed technologies that affect our everyday lives. Everyday devices like smartphones and computers would not exist without magnetism and electricity applied to a small scale.

Magnets repel or attract other magnets depending on the position of the poles of the magnet. If freely suspended, one pole will point toward the north. This pole is thusly named the north magnetic pole. The opposite pole, which is attracted to the south pole is called the south magnetic pole. It is impossible to separate a north and south pole as there are no magnets with only one polarity.

Try moving these magnets around and observing how they exert force on one another depending on their angle and distance.

Figure 5.12: The diagram presented on page 1 of the Faraday's Law lesson in the PhyAR2 application.

repelling." An illustration of this page is presented in Figure 5.12.

Ferromagnets and Electromagnets

On the second page of the Faraday application, an explanation of the different types of magnets is presented. This is presented in Figure 5.13

Magnetic Fields

On the third page of the Faraday application, a magnet that can be moved through a magnetic field using pinch-and-drag gestures in the Hololens, using an object with a tracker on it, or using the

What are magnets?

All fixed magnets attract iron, cobalt, nickel, and gadolinium. These materials are called ferromagnetic materials. They can be magnetized by exposure to an external magnetic field.

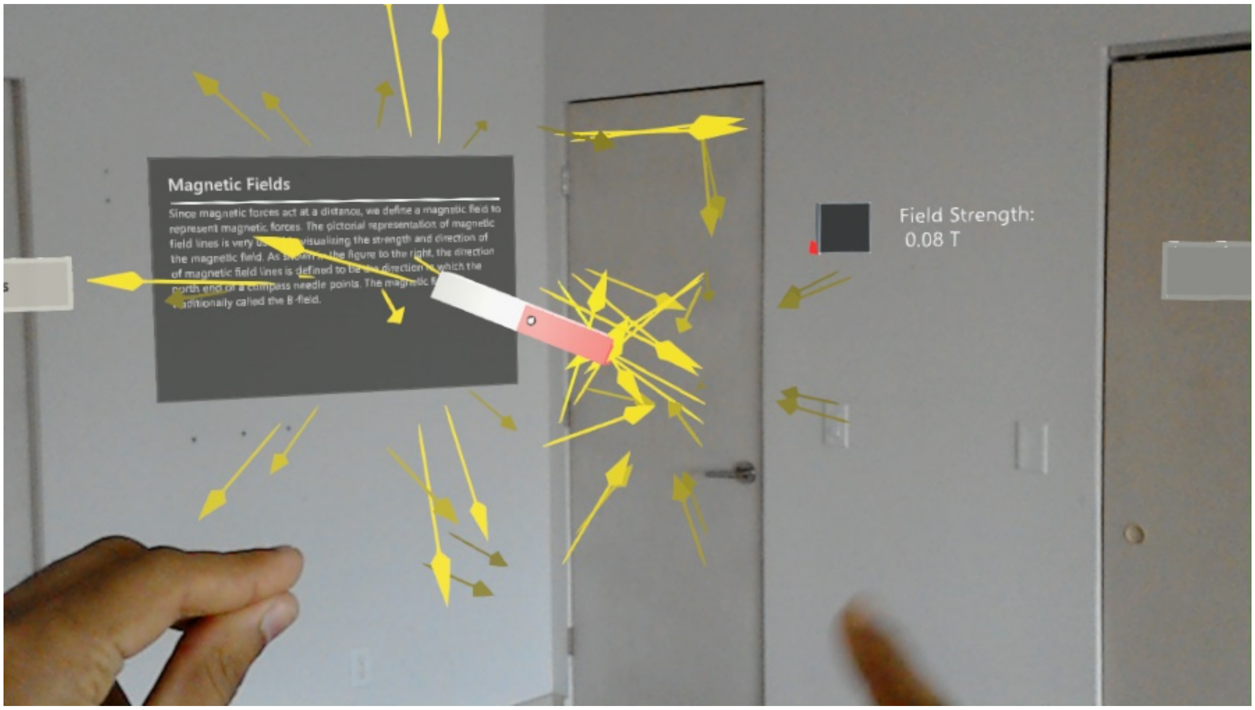
Electromagnets are like ferromagnets but are temporary. They only exert magnetic force when there is a current running through them. Electric current is the source of all magnetism.

Figure 5.13: The diagram presented on page 2 of the Faraday's Law lesson in the PhyAR2 application.

controllers in the VR configuration to translate, rotate, or scale the magnet. This is presented in Figure 5.14.

Magnetic Force

On the next page of the application, participants are presented with a basic illustration of magnetic force using a magnet and a vector field with a scope to check field strength at points around the magnet.



Magnetic Fields

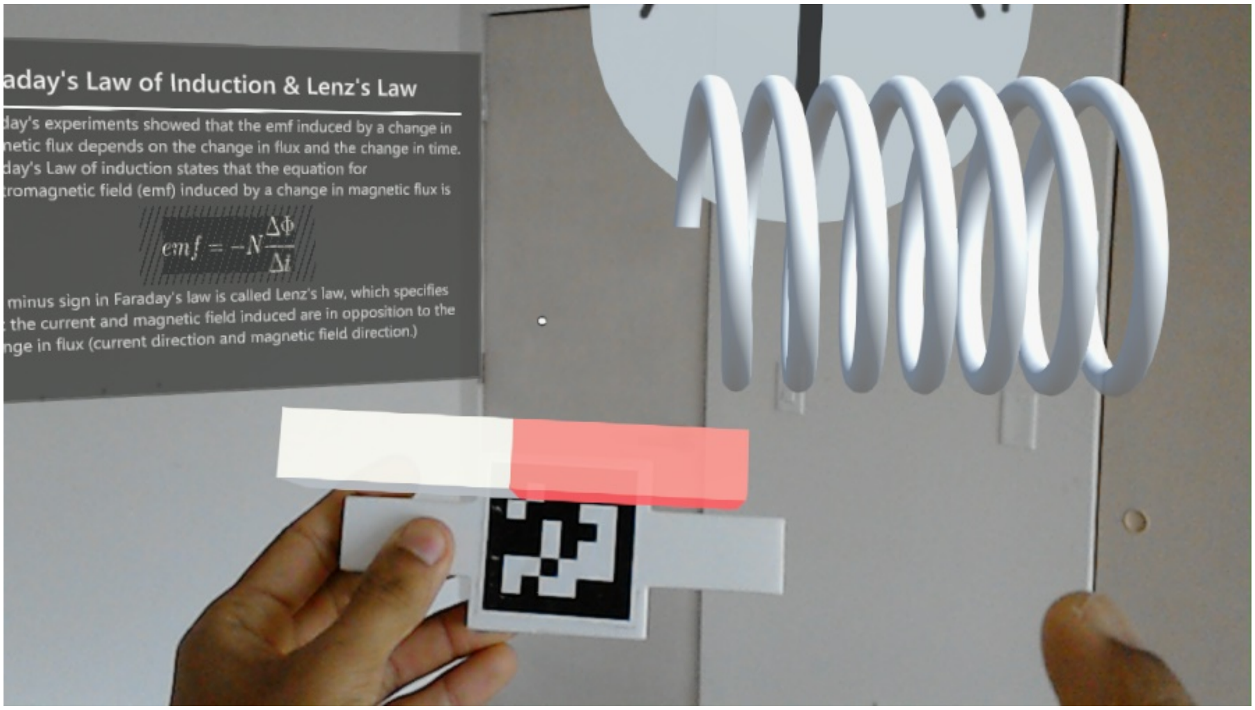
Since magnetic forces act at a distance, we define a magnetic field to represent magnetic forces. The pictorial representation of magnetic field lines is very u[illegible] visualizing the strength and direction of the magnetic field. As s[illegible] the figure to the right, the direction of magnetic field lines is defined to b[illegible] direction [illegible] which the north end of a compass needle points. The magnetic f[illegible] [illegible]aditionally called the B-field.

Figure 5.14: The diagram presented on page 3 of the Faraday's Law lesson in the PhyAR2 application.

Faraday's Law & Lenz's Law: Passing a Magnet through a Coil

On the next page of the application, participants are presented with a basic illustration of magnetic flux using a magnet, a voltmeter and an inductive coil. These three devices are used to present an induced current when the user moves the magnet through the inductive coil. The user is given free rein to move the magnet through the coil using physical objects. They are also free to manipulate the strength of the magnet to determine how the physical parameters of the simulation determine the induced current of the simulated run. The induced voltage follows the behavior of Faraday's Law, which states that

$$emf = -N\frac{\Delta\Phi}{\Delta t}$$



aday's Law of Induction & Lenz's Law

day's experiments showed that the emf induced by a change in
netic flux depends on the change in flux and the change in time.
day's Law of induction states that the equation for
tromagnetic field (emf) induced by a change in magnetic flux is

$$emf = -N\frac{\Delta\Phi}{\Delta t}$$

minus sign in Faraday's law is called Lenz's law, which specifies
the current and magnetic field induced are in opposition to the
nge in flux (current direction and magnetic field direction.)

Figure 5.15: The diagram presented on page 5 of the Faraday's Law lesson in the PhyAR2 application.

where emf is the induced voltage (in Volts), N is the number of turns of the coil, $\Delta\Phi$ is the change in magnetic flux, and Δt is the change in time. In layman terms, moving a magnet through a coil will induce different voltages based on the strength of the magnet being moved through the coil, and the speed at which the magnet moves. The minus sign in front of the equation is the component that is described by Lenz's Law, which states that the direction of the current induced by a changing magnetic field is such that the magnetic field created by the induced current opposes the initial changing magnetic field which produced it. These directions are specified by Fleming's Right Hand Rule. An example of this visualization is presented in Figure 5.15.

Evaluation

To evaluate PhyAR version 2, we first had to determine what questions we needed to be answered. The results of the study conducted with the students in the previous version of the application pointed towards a need to determine if AR has benefits when compared to VR, as some feedback received specified that the AR component was weak. Without real world integration, an easier task is to create a VR experience instead of an AR experience. Based on this idea, we decided to carry out a 2x2 mixed model study, where participants would be presented with both of the previously described lessons, but the presentation method (AR/VR) and order is randomized across participants. We wanted to determine if there was any appreciable benefit to tangible AR interactions compared to standard VR experience.

Participants and Apparatus

We recruited 16 participants (11 male, 5 female) from the University of Central Florida College of Engineering and Computer Science. Participants fell in the age range of 18 to 29, with a median age of 20, and a mean age of 21.6. Demographics information for the students recruited as participants in the study are presented in 5.1. Participants were required to be able-bodied and have 20/20 corrected vision. Participants were expected to be able to wear a Microsoft Hololens or HP Reverb without discomfort, and were expected to be able to properly execute the pinch gesture on the Hololens appropriately. Participants were compensated $10 for their time.

Procedure

Participants were asked about demographic information pertaining to their age and education background, whether they have taken physics courses (specifically Physics 1 and 2), how they perceived

Table 5.1: Demographic data of university students recruited for PhyAR2 study.[b] Note that blank spaces refer to courses that have not been taken by the participant.

Participant	Age	Gender	Calculus Req'd	Physics 1 Hard	Physics 2 Hard	Used VR?	Used AR?
P1	19	M	Yes			Yes	No
P2	27	F	Yes	Neutral	Somewhat Hard	Yes	Yes
P3	29	F	Yes	Somewhat Hard	Somewhat Easy	Yes	Yes
P4	29	M	No	Hard	Hard	Yes	Yes
P5	19	M	No			Yes	No
P6	20	M	Yes	Hard	Somewhat Hard	Yes	No
P7	20	F	No	Somewhat Easy	*Enrolled*	Yes	Yes
P8	19	F	Yes	*Enrolled*		No	No
P9	19	M	Yes			Yes	No
P10	20	F	No	*Enrolled*		Yes	No
P11	21	M	Yes	Somewhat Hard	*Enrolled*	Yes	No
P12	18	M	Yes			Yes	No
P13	20	M	No	*Enrolled*		Yes	No
P14	21	M	Yes	Hard	Hard	Yes	Yes
P15	19	M	Yes	*Enrolled*		Yes	No
P16	26	M	No	Easy	Easy	Yes	Yes

[b] Note that ”hard” is used in place of ”difficult” as on the collected demographics survey for visualization purposes.

the difficulty of those courses if they were enrolled or had completed them, and whether they have experience with AR or VR devices. The full content of this demographics survey is presented in Appendix E. Participants were then presented with a ten question aptitude pre-test (See Appendix H and I) to determine their baseline knowledge of the concepts to be discussed during the study, specifically Coulomb's Law and Faraday's Law. The participants were then randomly assigned to a group using Greco-Latin squares to ensure equal presentation of orders and prevent potential bias. Participants were then presented with the Hololens and HP Reverb devices and their features. The proctor then ensured that the participant was thoroughly versed with the gestures and limited field of view of the devices so that they are aware that they are not application specific issues.

All participants were presented with every concept from the study in a random, counterbalanced order to control for any learning effects between different concepts. Participants then proceeded through the structured lessons and completed the required tasks. After task completion, participants were presented with a post-study aptitude test (See Appendix H and I) and a post-condition questionnaire which had questions about usability and preference using a Likert scale and free response questions about positives and negatives of the concept and presentation method (See Appendix F). A UMUX-Lite usability evaluation is also coded into the Likert scale responses in the form of two questions about meeting requirements and ease of use. After all of the tasks are completed, participants completed a final survey where preference information was collected, with a specific binary preference question asked about AR/VR and preferred lesson (See Appendix G). Participants were then asked about their opinions about the application overall and if there were any shortcomings of different components. The study was allotted a 60 minute time slot. Participants typically completed the procedure in 45-60 minutes. Participants normally spent between 5-10 minutes within each headset during the study conditions.

Hypothesis

Based on existing results from the previous two studies and existing findings from the literature, we present the following hypotheses:

- **H1:** Participants will have significantly better aptitude score changes in the AR condition than the VR condition.
- **H2(a):** Participants will prefer the comfort of the VR headset to the AR headset.
- **H2(b):** Participants will prefer the larger field of view of the VR headset to the narrow field of view of the AR headset.
- **H2(c):** Participants will prefer the controls from the VR condition to the tracking used in the AR condition.

Results

The results of the study are presented in this section. We split the results into the Likert scale feedback, the post-condition free response surveys, and the exit interviews. The last of these included direct preference information about AR vs VR.

Likert Scale Feedback

A graph illustrating the responses to our Likert scale questions is presented in Figure 5.16. Because the study does not follow a traditional between subjects, mixed model study, we elected to forgo an omnibus test. We were not interested in interaction effects. Our primary interest was a direct comparison between AR and VR. The concepts were treated as the grouping variable and the ordering was ignored because our groups were counterbalanced and of equal size. The results of these two tests are presented in Tables 5.2 and 5.3 for Coulomb's Law and Faraday's Law, respectively. From the results of this test, we can see that there are no significant differences between the two presentation methods in any of the Likert scale responses except for Easy to use, Motivating, and Meets requirements in the Faraday's Law lesson. Two of these, Easy to use and Meets requirements, are the constituent components of the UMUX-Lite usability metric, which also presented a significant result, with the AR condition falling below the mandatory score of 50 to be considered usable. However, as this response specifically arose in the Faraday's example and was not present in the Coulomb's example, we can predict that it was likely due to the design of the lesson and not inherent to the AR device or Faraday's Law concept. Santos et al.'s meta-analysis of the literature has stressed the importance of proper lesson design in AR experience acceptance [63].

In all other instances, we can see that there was little meaningful difference between the two

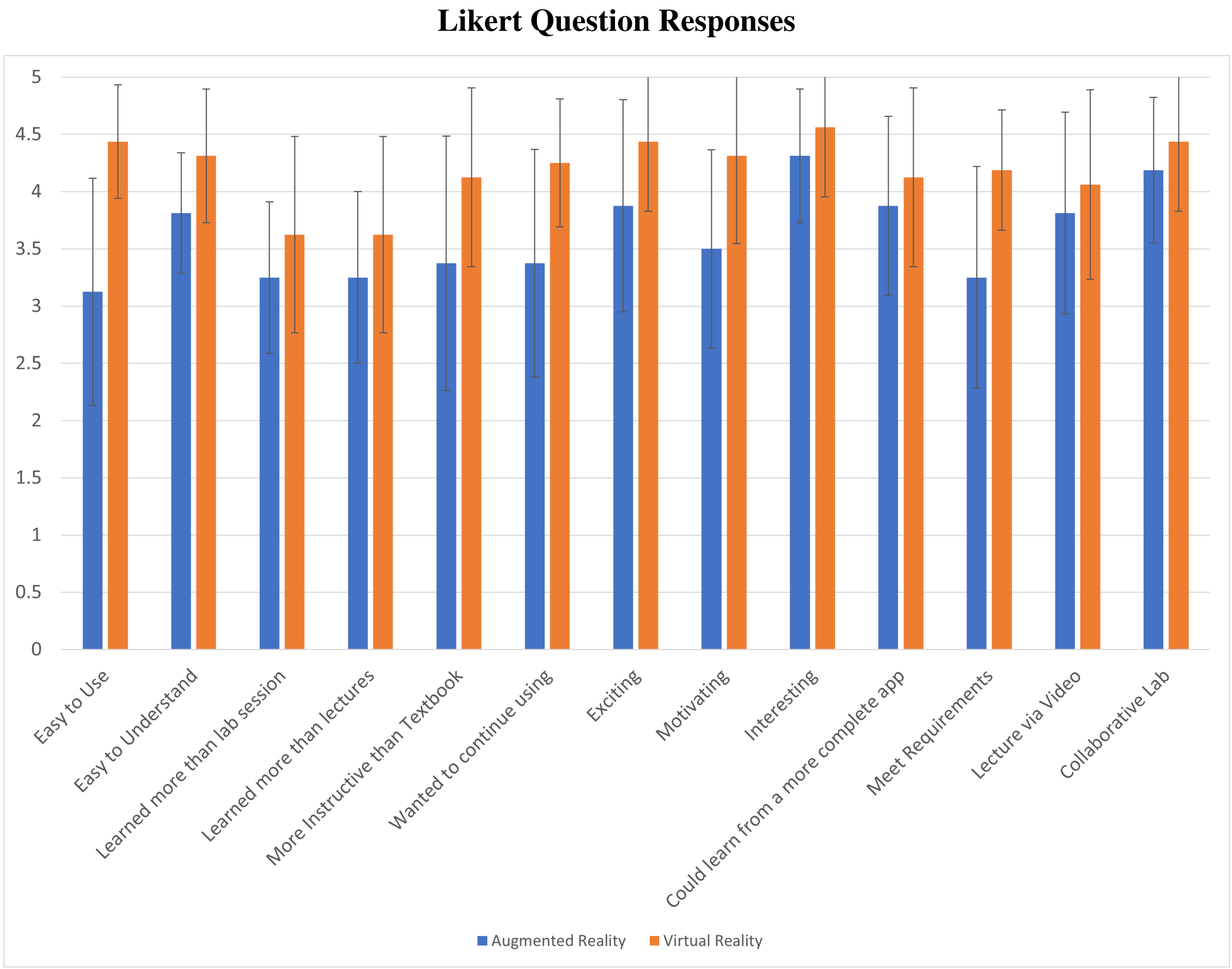


Figure 5.16: Mean responses to Likert scale questions from the PhyAR2 study.

presentation methods, which could likely be attributed to some degree of novelty effect and the study being too short for any explicable frustration to arise.

Aptitude Test Results

We calculated some estimates of learning results based on the aptitude score changes. The mean pre-condition score for Faraday's Law was 5.81 ($SD = 1.76$) and for Coulomb's Law was 5.69

Table 5.2: Results of Mann-Whitney U test for Coulomb's Law applications in AR and VR.

Response	Virtual		Augmented		Statistic	p-value
	μ	(σ)	μ	(σ)		
Easy to use	4.29	0.45	3.44	0.96	$U = 47.0$	$p = .08$
Easy to understand	4.43	0.49	4.00	0.47	$U = 43.5$	$p = .13$
Learned more than lab session	3.71	0.88	3.44	0.50	$U = 35.0$	$p = .72$
Learned more than lectures	3.71	0.88	3.44	0.68	$U = 36.0$	$p = .62$
More instructive than a textbook	4.29	0.45	3.78	1.03	$U = 40.0$	$p = .37$
Wanted to continue using	4.14	0.64	3.22	0.92	$U = 49.0$	$p = .06$
Exciting	4.29	0.70	3.89	0.87	$U = 39.0$	$p = .42$
Motivating	4.14	0.83	3.56	0.83	$U = 42.5$	$p = .24$
Interesting	4.43	0.73	4.44	0.50	$U = 33.0$	$p = .91$
Could learn from a more complete app	4.43	0.49	3.78	0.79	$U = 45.5$	$p = .10$
Meet requirements	4.14	0.35	3.78	0.79	$U = 38.5$	$p = .37$
Lecture via video	4.14	0.35	4.11	0.57	$U = 32.0$	$p = 1.0$
Collaborative lab	4.43	0.49	4.22	0.63	$U = 36.5$	$p = .59$
UMUX-Lite	75.13	5.92	65.33	11.98	$U = 47.0$	$p = .10$

($SD = 3.11$). To evaluate learning results, we transformed the pre- and post- condition aptitude test result difference into an integer value in the range of -10 to 10 by subtracting the post-condition score from the pre-test score. We divided this along each of the presentation methods and present them in Table 5.4 and found that there were no particularly meaningful differences in the means. One outlier who was presented Coulomb's Law in VR had an eight point shift in their score which distorts the value presented here. When excluded from the data, VR Coulomb becomes ($\mu = 0.57, \sigma = 1.81$).

Post-Condition Free Response Survey

Overall, feedback from participants was generally positive for each of the polled questions. These questions can be found in Appendix G of this document. Half of the participants had some degree

Table 5.3: Results of Mann-Whitney U test for Faraday's Law applications in AR and VR.

Response	Virtual		Augmented		Statistic	p-value
	μ	(σ)	μ	(σ)		
Easy to use	4.56	0.50	2.71	0.88	$U = 59.0$	$p < .01$
Easy to understand	4.22	0.63	3.57	0.49	$U = 47.5$	$p = .07$
Learned more than lab session	3.56	0.83	3.00	0.76	$U = 42.5$	$p = .24$
Learned more than lectures	3.56	0.83	3.00	0.76	$U = 42.5$	$p = .24$
More instructive than textbook	4.00	0.94	2.86	0.99	$U = 49.5$	$p = .06$
Wanted to continue using	4.33	0.47	3.57	1.05	$U = 43.5$	$p = .16$
Exciting	4.56	0.50	3.86	0.99	$U = 44.0$	$p = .16$
Motivating	4.44	0.68	3.43	0.90	$U = 50.0$	$p < .05$
Interesting	4.67	0.47	4.14	0.64	$U = 45.0$	$p = .12$
Could learn from a more complete app	3.89	0.87	4.00	0.76	$U = 30.5$	$p = .95$
Meets requirements	4.22	0.63	2.57	0.73	$U = 58.5$	$p < .01$
Lecture via video	4.00	1.05	3.43	1.05	$U = 41.0$	$p = .32$
Collaborative lab	4.44	0.68	4.14	0.64	$U = 39.5$	$p = .38$
UMUX-Lite	77.97	8.37	49.60	8.37	$U = 62.5$	$p < .01$

Table 5.4: Results of the pre-/post- aptitude test difference descriptive statistics.

Condition	μ	(σ)
AR Coulomb	0.25	1.04
VR Coulomb	1.50	3.11
AR Faraday	1.25	1.98
VR Faraday	0.75	1.39

of experience with an existing piece of education software. This helped to provide them with a comparative frame of reference for the feedback they were providing.

Participants provided similar reasons for liking both of the conditions. For both AR and VR, participants listed the interactivity of the applications as a positive. More specific reasons for liking the applications included being able to manipulate one or all three axes of the virtual objects, allowing for physical grasping of tracked objects in AR, and the novelty of it (AR and VR). One participant specifically stated "Seeing the graphs and the force between the objects and moving them aided in my understanding" when talking about the AR Coulomb's Law lesson. Another participant reported liking the way the vectors and graph around the magnets updated in the VR Faraday's Lesson. Another participant specifically mentioned enjoying the 3D component of both the AR and VR presentation methods, stating "textbooks can only show 2D cross-sections of concepts like this, but this application let me interact with a 3D concept in a 3D environment."

Participants did have some points of contention with both applications. For VR, two participants felt like the VR headset was somewhat heavy. Another reported that they would have preferred to be able to see a table or their environment in VR to allow them to take notes. For AR, there were more diverse criticisms. First, participants were not fond of the limited field of view of the Hololens (3) and the frame rate (2) drops caused due to the marker tracking algorithm. Three participants reported issues with blurriness of the content in AR.

Like in the PhyAR version 1 study, participants were asked to provide what settings they would most like to use a similar application. For VR, 13 of the 16 participants reported wanting to use the device for individual study, 10 of 16 reported wanting to use it for collaborative projects, and 12 of 16 wanted to see instructors use it for demonstration purposes. For AR, 13 of the 16 participants reported wanting to use the device for individual study, 11 of 16 reported wanting to use it for collaborative projects, and 8 of 16 wanted to see instructors use it for demonstration purposes. We conclude that the perceived utility to the participants courses was similar between the two display types.

We also asked for more specific use cases that the participants felt would help them. Participants tended to favor providing more techniques for instructor illustration and collaborative settings regardless of headset. Specifically those concepts which are difficult to visualize, which is another reiteration of feedback which has been collected in previous studies. Group work is another repeated topic regardless of selected headset, written in 3 times for each condition.

Participants were asked about if they would prefer to use an AR/VR headset instead of running a traditional lab. After the AR condition, ten out of the 16 participants thought that physical labs would be better because of the reliability if the physical world and the tools we used to measure it. After the VR condition, seven out of the 16 participants thought that the physical labs were better in most cases. The reasons given for favoring physical labs emphasized error margins and uncertainty about the transfer of learning from a virtual setting to a physical one. However, three participants did specifically mention that it would be better to use AR/VR for specific topics that have forces that are unseen or difficult to measure. In cases were AR/VR was mentioned as the preferred alternative, participants mentioned that collaboration and novelty would make the content more fun and exciting. Two participants specifically mentioned the COVID-19 pandemic considerations in selecting AR/VR as their preference.

Finally, we requested feedback about ways to improve the experience of using these devices. One participant mentioned note-taking in VR as a difficult task. They stated that it is quite different from physical labs where students are expected to refer to a lab notebook regularly to write out repeated measurements from an experiment. Another participant requested a sort of scaffolding to the visualizations in the form of preset values that would help to illustrate mathematical relationships between different variables, such as the inversely proportional relationship between distance and force in Coulomb’s Law. In VR, participants mentioned wanting a wireless headset because of the weight of the device. In AR, participants wanted the device to be better in the usual ways: better field of view, better frame rate, easier interaction.

Post-Study Preference Survey

Participants were asked to choose which visualization method and concept they preferred. Three out of the 16 participants reported that they preferred the AR headset. All participants stated that this preference was because they liked being able to see the real world with the augmented objects. The other 13 of the 16 participants preferred the VR condition for various reasons that echoed responses from the previous studies. Generally, the participants reported that the device was easier to use (9 out of 13), it was easier to visualize the concepts (4 out of 13), the field of view was better (4 out of 13), and the controls were better (3 out of 13).

Participants preferred the Coulomb’s Law demonstration, with 13 of 16 preferring it to the Faraday’s Law lesson. This result was true regardless of presentation method. If it was in AR, participants enjoyed interacting with the point charges using the Fiducial markers, and they thought the tactility of the objects was beneficial. One participant reported that explanation was clearer in for the Coulomb’s Law lesson than the Faraday’s Law demo. Still, those participants that reported enjoying the Faraday’s Law lesson stated that they preferred the concept overall and thought it was helpful to see it presented in 3D.

Discussion

The results of this study paint an interesting picture for what role we expect AR and VR to play for students enrolled in physics courses. Revisiting the hypothesis we formulated prior to the study, we can draw some conclusions about our participants performance and preferences.

Hypothesis 1: Based on the results of the study, we can say that our first hypothesis, relating to learning results in the form of pre- and post-condition aptitude scores, is inconclusive. We did not find any significant difference between the two conditions with regard to aptitude scores.

Hypothesis 2(a): Participants overall preferred the comfort of the VR headset.

Hypothesis 2(b): Participants preferred the larger field of view of the VR headset. Participants frequently cited the inability to see all content within the AR condition due to limited field of view as a negative aspect of the AR condition.

Hypothesis 2(c): Participants preferred the controls from the VR condition overall because of the responsiveness of the buttons and accurate tracking, but did see benefit to the embodied interaction with the tracked objects from the AR condition.

We can draw some conclusions based on these results. First, that responsiveness and ease of use heavily impacted user preference, as expected. Many of the participants mentioned enjoying the tactile feedback of handling the marker tracked shapes in the AR condition. This is something that the VR condition can't easily do as the users are typically moved into a different environment when they are in a virtual scene. If that is the case, perhaps it would be best to instead build some method of providing better tactile feedback to users in a VR environment to capture the best components of AR based interfaces. This allows us to form an idea for future exploration that perhaps we can still provide a large portion of the benefits of spatial and contextually aware presentation of information which is a known benefit of AR in a VR experience instead.

Another finding from this study was that the participants did not particularly care for the Faraday's Law lesson that was built for this study. Two commonly cited problems stem from the lesson not being as concise as the Coulomb's Law lesson, which focused specifically on the text of Coulomb's law, its effects, and nothing else. This is an important detail for potential developers because it shows that simply placing some content in AR is not enough to make it enticing or beneficial to the learning experience. The content selected must still be carefully curated by some sort of domain expert who can ensure it is of proper scope and depth. In designing the two conditions, we referenced two textbooks, one by OpenStax for College Physics [66], and the other by Siyavula for Grade 11 [51]. We note here that Coulomb's Law covers a single section and Faraday's Law and its precursors in magnetism are covered over one complete chapter and an additional section. This is likely far more content than should be glossed over in a short lab like the one presented during this study.

Another consideration to take away from this study relates to the COVID-19 pandemic, which we will speak at length about in the discussion chapter. The pandemic and its effects on student opinions cannot be understated. The feedback from some questions, such as AR/VR vs physical lab have shifted dramatically from the previous study involving university students (Study 2). This is likely because many of these participants were accustomed to in-person learning and traditional classroom/lab settings and have been segregated from that for an extended period of time. This could be seen as a confounding variable on much of the feedback received in this most recent study. It would have been beneficial to have had a question specifically about what type of learning the participants were accustomed to prior to the pandemic, which type they preferred prior to beginning the study, and then finally polled them for how they would want to see AR and VR technologies used in a course/lab after completing the study. As of now, we will accept that the results are likely biased and/or inconclusive due to a confounding variable.

Lastly, we would like to touch on content creation. While the Mixed Reality Toolkit is a brilliant tool for developing AR/VR application for developers, it does little to simplify the process of creating content that is meaningfully integrated with the environment. The Hololens 1 does not have any sort of object tracking method built in. The object tracking used in these AR applications was brought in from OpenCV, incurring significant computational overhead. This was detrimental to user experience because the frame rate of the Hololens was far below the minimum recommended 60 fps that is recommended for head-worn content [59]. This means that to make a truly world-state aware AR application, the device must push processing off to a remote system to preserve a positive user experience. This may change in the future with newer hardware, but even the Hololens 2 does not feature object tracking for grasped objects. Perhaps another pivot towards desktop AR headsets would improve this experience.

Educators' Perspectives Revisited

After collecting feedback from this second group of students, it was necessary to step back and collect feedback from educators once again to determine how this new iteration of the prototype compared to PhyAR version 1, which featured similarly scoped applications to those presented in Study 1. We contacted two practicing educators, one who had participated in Study 1 (T6) and one who had not seen the application at all (T7). Due to COVID-19 restrictions, the educators were interviewed remotely via email and phone calls. During these interviews, two videos were presented to the educators: the first included demonstrations of the content a PhyAR version 1, and the second included an expert user navigating the PhyAR version 2 lessons. These videos were used to present a before-and-after example of how both student and educator feedback had informed the design of the application and content selection. After being presented with both videos, the educators were asked a set of questions, presented in Table 5.5, pertaining to their opinions of the applications. Further elaboration beyond these questions was encouraged.

Table 5.5: Questions asked during the educator retrospective interviews.

	Free Response Questions
Q1	What parts of the applications do you like?
Q2	What parts of the applications do you dislike?
Q3	Do you think that, if provided with appropriate tools, you could create your own content
Q4	Where there features you would have liked to see that were not presented in the videos or the applications?
Q5	Is interaction with real-world objects necessary to elicit positive learning experiences in students? How do you feel the real objects impact student motivation?
Q6	Are there things that students often have trouble understanding that this sort of tool could assist?
Q7	What would the ideal version of an AR education application look like in your classroom?

Q1: Positive Comments

Both interviewed educators liked the marker-tracking interaction modality selected in the PhyAR version 2 application. One of the educators specifically likened the application to a modernized PHeT Lab but with the added benefit of 3D visualization:

> *These simulations, in particular the electric fields one reminds me of the PHeT Labs but just modernized and updated for an evolving world. The AR version does a better job conveying the structure of the field as it projects into 3D space which the PHeT Lab cannot do. (T7)*

T7 stated specific positive elements from two of the demonstrations: Kinematics and Doppler Effect. In the kinematics demonstration, they liked the use of toggles and sliders as methods of input, which they predicted would ”assist learners’ problem-solving and independent practice.” They stated that the Doppler effect example added a physical representation to the characteristics of a propagating wave in real-time. This, in combination with a tangible object to hold, was seen a good feature to include to the application.

Q2: Negative Comments

Both educators worried that there could be too much information presented in some applications, like the magnetic field demonstration. They wanted to see fewer vectors to not overwhelm students. Many of the shortcomings of the applications trended towards AR taking a supplementary role in complexity of visualization and classroom use, much like the participants in Study 3 reported. Both educators preferred emphasizing real world laboratories when possible, with one specifying that ”students going into the fields of engineering and physics should display kinesthetic proficiency, limitations withstanding.”

Q3: Content Creation

For content creation, one educator explicitly stated that they did not have enough time or want to learn to use tools for creating content:

> *To be honest, teachers are so busy, I would not want to build my own content. Having pre-designed content organized and ready to go that we can share and use with students is what we want. (T6)*

The other educator (T7) pointed out that many of their colleagues had experience with programming and could see the formation of a community-run repository of AR content for use in classrooms, which would be similar to the curated PhET lessons [58]. Specific concepts that the educators mentioned as areas for future development were kinematics problem-solving and electrical circuits. One educator asked for a tool for slowing down and pausing simulations and a tool for measuring to assist in calculations.

Q4: Missing Features

Some specific features requested by the interviewed educators included:

- Force Diagrams
- Pause and Resume
- Measurement Tools
- Problem Integration

Specific concepts that the educators mentioned as areas for future development were kinematics problem-solving and electrical circuits. These features would be useful to better capture the real world working process of physics laboratories for students.

Q5: Necessity of Real-World Objects and Impact on Student Motivation

When asked about the importance of providing real world objects for the students to interact with inside the AR configuration, both educators responded strongly in favor of it being an important component for student motivation and engagement:

> *Absolutely, 100% yes. When students are able to interact and manipulate with physical objects or content through labs or stations it is incredibly beneficial to their learning...*

> *I have found in my years of teaching, students struggle the most with concepts of things that they cannot physically touch [sic] or see, such as physics concepts. (T6)*

> *Yes, often times I have students telling me or venting frustration as to why mathematics is taught in a vacuum without a greater emphasis on applications. Some students need affirmation that the knowledge they are learning is useful in the real-world to even engage them. Real-world object interaction helps close that gap. (T7)*

These comments echo similar feedback we collected from the educators who provided feedback in Study 1. T6 stated that there was a sense from students that ”the mathematics found in physics feels arcane, esoteric, and at times simply feels like magic.” They went on to state that there was a need for an extra step to help students who favor inquiry-based learning to have more free form tools for exploring novel concepts.

Q6: Concepts Students Find Difficult to Understand

Specific concepts were described as difficult to understand by T7:

> *Much of physics falls into the paradigms of visual, kinesthetic, logical and naturalistic (pattern) learning style. AR programs can appeal to students who gravitate towards being visual and naturalistic learners who otherwise might be a bit weaker with logical thinking or mathematical thinking or those with limitations to hands-on approaches. Certain abstract concepts such as electricity, magnetism, gravitation, fluid flow are rooted in analysis of vector fields which are very tough on a white-board to portray and even images sometimes fail to portray them in 3D. This can go a long way in helping*

> *students understand concepts as divergence, curl, the gradient and their impact on physics. (T7)*

We founds similar feedback from the educators in Study 1 and the Students in studies 2 and 3. Enabling 3D visualization is a great help to those students who struggle with abstract or invisible concepts.

Q7: Ideal AR Education Application

Both educators laid out an ideal AR education application that was able to visualize the invisible. T7 provided an example of how it would fit in a course:

> *An ideal AR should be a supplement to the classroom very much like traditional labs or practical activities are. A day with AR could have students following along with instruction from a teacher or professor and witness scenarios in real time that are otherwise tedious, time-consuming to draw or where images cannot fully portray the scope of the situation. Given physics as a science is governed by positional and time (in)dependency of systems, having students being able to visualize this in real-time would lend to heightened understanding as they can witness dynamic systems in the truest and literal sense. A teacher or professor can instruct students with a prompt to follow along in AR, perhaps seeing simulations or problems otherwise difficult to capture or replicate in the classroom. (T7)*

Their vision for future versions of PhyAR would be as a tool for reinforcement independent of lectures and in-person laboratories, though with more emphasis on exploration and demonstration. A quick reference to the prerequisite knowledge included in any application was also seen as something that would be beneficial to learners. Overall, we found consistent feedback between the educators recruited for these interviews and the students who participated in Study 3.

Conclusion

In this chapter, we presented the results of a comparative study between an AR and VR version of a physics education application featuring two specific concepts. Our findings show that there is little difference between presenting content in AR or VR when comparing test results on an aptitude test, but further evaluation is required. We predict that some students will find benefit from the additional real world integration AR allows, but overall, the ease of implementing lessons in VR could sway many developers to favor creating VR content instead.

CHAPTER 6: DISCUSSION

The purpose of the three qualitative studies was to determine potential use cases for augmented reality for physics education in secondary and post-secondary school settings, and to determine in what specific ways users might benefit. We first collected feedback from a set of interviews of secondary school educators with experience teaching physical sciences, which we presented in Chapter 3. In Chapter 4, we created a prototype application which was used to collect feedback from a group of university students on how they would respond to the use of a similar application in their courses. We then implemented some recommended improvements and made a comparison to a VR equivalent to determine if there were any perceived benefits to AR specifically, which we presented in Chapter 5. In this chapter, we discuss how the major findings of these three studies relate to the literature on AR software for education, best practices for presenting new content to learners, and classroom use cases for AR. This chapter also includes some discussion of limitations of the studies conducted.

The main purpose of this chapter is to summarize and present how the previous studies have addressed the research questions:

- **RQ1:** How does presenting students with physics concepts in AR benefit their learning experience and performance?
- **RQ2:** How does having high levels of integration with existing physical objects affect a student's understanding of unfamiliar material?
- **RQ3:** How does tying AR visualizations to physical objects assist students in understanding new physics concepts when compared to a VR visualization with controller-based interaction?

In addressing these questions, we also found the following themes repeated in qualitative feedback collected from students and educators: (a) most participants reported that they appreciated the ability to physically interact with the concepts they were learning, (b) 3D visualization of new concepts was beneficial, (c) both students and educators felt that AR would best fit as an intermediate step between lectures and labs. These themes point towards broad methods of integrating AR in a classroom.

Interpretation of Research Questions

The results of the two student studies provide us with sufficient information to begin to draw some initial conclusions about each of the three research questions.

Effect of Presentation of Physics Concepts in AR

Based on the results of our last study, we can not make any strong claims about the aptitude or classroom performance of the AR figures presented. However, as it pertains to learner experience, we found positive preference responses across the board from all participants. This finding is consistent with the existing literature which presented new concepts in AR [2, 16, 63]. Cai et al. [18] found that students with higher levels of self-efficacy, experienced better learning rates with AR and clearer conception of new mathematical content, but all students experienced enhanced learning to some degree. It is important to note that participants often have more patience for novel presentation of information [33].

Effect of Integration of Real World Objects on Understanding

Based on the results of our last study, we found that there was no quantitative benefit to integrating real world objects with the AR experience. Participants aptitude scores were consistent regardless of being placed in VR with virtual objects or in AR with real objects. This result is consistent with existing literature, which found that aptitude was not different, but experiences were generally more positive and motivation was greater in students who experienced lessons in AR [71]. The result found in Study 3 was influenced by the design of the tracked objects as they were not facsimiles of real objects, but placeholder objects with markers placed on them. Participants often cited the tracking as being inconsistent, which caused friction when exploring the Faraday's Law and Coulomb's law lessons.

Preference of AR Visualization vs. VR Visualization

Participants in the last study generally preferred the VR experience to the AR experience along multiple metrics, including general preference, usability scores, and qualitative feedback. The reasoning for this is multifaceted, including improved field-of-view, better tracking, higher resolution, and more responsive controls. In their qualitative feedback, interaction was an oft cited shortcoming of the AR application in Study 2 which we attempted to correct for in Study 3 using the tracked objects with markers attached to them. What we found was that while marker-tracked objects were better than gaze-based interaction was, marker-based tracking could not compare with the controller-based interaction that the VR condition used for reliability. Clearly visualization is an enticing feature for learners, but meaningful, reliable interaction was what caused most of the students to prefer the VR condition. Kang et al. [42] also found no preference between AR and VR visualization in their study with younger children, but the age of participants and complexity of the concept could influence that result.

Interpretation of Prevailing Themes

Three themes frequently arose within the feedback collected from educator and student participants.

Interaction with Concepts

Both students and educators welcomed the opportunities to manipulate content in all three prototypes (HoloPhysics, PhyAR, PhyAR2) using gaze-based interaction or marker-based tracking. Though the controller feedback enabled in Study 3's VR condition outperformed the gaze and marker based interaction in terms of user acceptance, it can be expected that improvements in technology will bridge this gap and better enable users to grasp and manipulate virtual content in the real world. There was a proprioceptive element to the AR scenarios that was frequently cited as a nice feature to have, regardless of concept presented. Our design recommendations following Study 1 did not address physical interaction, as it was not a frequently cited theme. However, we can point towards the feedback collected from students and educators following Study 3 that there is a desire to provide some degree of physical (tangible) interaction where appropriate, even if only as a way to encourage inquiry.

3D Visualization vs. 2D Figures

Participants in all studies found benefit in the presentation of concepts in three dimensions, in lieu of traditional presentation methods using static figures in textbooks or 2D figures on flat screens. Educators specifically stated that many of the concepts visualized in the latter studies, such as magnetism, are often difficult for students to grasp from the figures presented in textbooks. Based on this, we find that the design recommendations presented following Study 1 remain important. Emphasizing difficult concepts remains a good practice for developing interesting content in AR. The educators interviewed after Study 3 also emphasized the importance of the visualization enabled by the AR headsets. Students are often presented with a few static figures as their introduction to a new concept and then are expected to conduct a laboratory without seeing or understanding the forces at play in that laboratory.

Augmented Reality as a Reinforcement Tool

Through the course of the three studies conducted, a broad spectrum of use cases were presented by participants, both educator and student, regarding how best to integrate AR with a course. The teachers interviewed during Study 1 and in the retrospective interviews after study 3 pointed out that it would be best to use AR as a tool for demonstration via augmented lecture or reinforcement tasks independent of traditional laboratories. In a way, the teachers opined that AR should be treated as supplemental instruction. During study 2, student participants frequently stated that they could imagine a physics course which exclusively used AR laboratories instead of traditional in-person labs. Student opinion changed drastically in those students recruited for Study 3, which occurred during the COVID-19 pandemic, which will be discussed in a separate section to follow. Students who participated in Study 3 provided similar preference to the teachers from Study 1, leaning more towards using AR as a tool for reinforcement instead of a replacement for traditional laboratories. This idea of reinforcement has frequently been presented in existing literature [69] as an ideal use case, similar to those computer-based models presented via PhET [58].

Impact on Existing Work

Generally, the results of the studies conducted over the course of this dissertation are consistent with similar studies in to the AR applications using tablets [29, 42] or other hardware [4]. Specifically we found that there are similarities in our results with regard to motivation, interest, and excitement.

Fidan and Tuncel [33] and Barma et al. [6] discussed the shift in technical expertise in learners as a motivating factor in encouraging adoption of AR/VR experiences in the classroom, specifically due to the prevalence of digital natives in modern classrooms. Our results echo this idea, as learners often came from a generation that has always had access to an Internet connection and computers as learning tools. So long as the application meets minimal usability requirements and the hardware does not hinder the completion of their tasks, it will likely be positively received by this new generation of learners.

Milgram's mixed reality continuum [56] is often cited as well suited to classifying mixed reality experiences. In Chapter 3, we proposed *environmental integration* as an alternative method of measuring the degree to which a mixed reality experience allows for embodied experiences with the real world. We feel that it is better to provide finer detail about how an experience leverages tangible, visual, and spatial information within a real world space. Other recent work also discusses how the Mixed Reality Continuum is more complex than a one-dimensional line, and is likely closer to a multi-dimensional space broken down along information presentation, visual fidelity, opacity, and tangible interaction [10, 40, 52, 54, 57]. We feel that given today's devices and the devices to come in the next decade, environmental integration's three axes are likely sufficient for describing existing and upcoming devices and experiences without wandering into the domain of science fiction.

Limitations

As we alluded to in the previous sections, content creation is far and away the hardest task in AR. For perspective, the VR version of Study 3 took less than 10 hours to create, compared to greater than 40 hours for the AR version. We point to the relative maturity of VR development tools compared to AR tools today. We also can point to AR simply being a more difficult modality to develop interesting content with the default tools. These problems might be alleviated with upcoming tools from Google and Apple, though those currently emphasize smartphone based applications.

Physical labs are plainly superior to AR for most simple applications in Physics 1. The ”Augment the visible” design consideration we discussed in Chapter 3 is the most applicable for concepts like kinetic energy and projectile motion. In those cases, the most beneficial augmented content we can conceive is the visualization of a force diagram over a physical lab as a form of guidance on the nature of forces. However, this is more using AR as supplement to the lab and not as the main feature of the lab.

We hypothesize that scaffolding is required to ensure that students are maximizing the learning results in AR. Our studies were primarily more sandbox oriented, even though study 3 had a specific flow and covered concepts in an iterative manner. Yet we felt that students would benefit from some more structure problems and pre-defined ”keyframes” for the diagrams to snap to help emphasize the important details in the scene.

Lessons Learned

One of the main takeaways from the studies conducted would be that students and educators responded positively to any alternative method of presentation. The reasons varied depending on what version of the PhyAR prototype they were presented with, but most participants reported that they appreciated the ability to interact with the figures, either from a conceptual understanding level, or being provided with a 3D visualization of what would traditionally be a static 2D image in a textbook. In this way, we can say that while there is certainly a novelty effect to AR element of the work, the utility of an intermediate step between lectures and labs is clear. The prototypes presented here and similar systems from other existing literature would fit that requirement.

Interaction was a repeatedly cited shortcoming of the AR application in Study 2 which we attempted to correct for in Study 3 using the tracked objects with markers attached to them. What we found was that while marker tracked objects were better than gaze-based interaction, marker-based tracking could not compare with the controller-based interaction that the VR condition used for reliability. We reiterate here that visualization is an enticing feature for learners, but meaningful, reliable interaction was what caused most of the students to prefer the VR condition. This shortcoming has been somewhat relieved in the Hololens 2, which features full hand tracking to enable bi-manual grasping and dragging. While a great improvement, this still does not exhibit tangible feedback that VR controllers or tracked real objects allow. We expect that future AR devices will be more capable of enabling this type of interaction reliably.

Based on results from the final study, VR applications could also be a beneficial tool for those who already have taken advantage of the newly arising low cost VR systems flooding into the consumer segment. Students reported preferring the wide field of view, input reliability, and tactile feedback enabled by the HP Reverb controllers, so it is likely that until there is a dramatic improvement in AR device field of view and interaction techniques, there are likely some benefits to focusing on VR applications for now. We noticed this during the AR condition experiments in Study 3, as there were frame rate problems in AR that were detrimental to the experience, even though it was not clearly stated by most of the participants.

We reiterate that these AR/VR approaches likely are best suited as an additional tool for learning physics instead of a full replacement for in person laboratories. We note that many participants in both Study 2 and 3 mentioned that they thought that the AR/VR conditions were good for invisible force visualizations like electrical fields, but they thought that the devices limited their ability to take notes and collaborate with those around them. They also mentioned in various ways that it complicated some simpler concepts, like the basic coefficient of restitution interactive figure from Study 2. Based on this, we can recommend that any force that is not visible or relies heavily on 3D vector mathematics in labs would benefit from this additional explanation. Electricity, Magnetism, and waves are the broad concepts that are presented in Physics 1 and Physics 2 that we feel would best make use of the additional illustration. Students in Study 3 leaned heavily on a desire to have in person labs because they thought it would transfer to other real world problems they might experience in later courses, an idea echoed in retrospective interviews with educators conducted after Study 3. All participants in Study 3 were students majoring in Information Technology, Computer Science, or Computer Engineering.

Content Creation

As researchers first, we experienced problems with content creation. There is an entire subfield of the education field that emphasizes the development of appropriate content for specific pedagogical results. We initially felt that this work was beyond the scope of this dissertation, but relent that there was clearly a need to leverage the knowledge of that domain when developing content for our studies. Based on this observation, we would recommend that any future researchers or application developers who want to emphasize AR or VR content as their devices should think about enlisting the aid of practicing educators in the creation of their content. Alternatively, it would be beneficial to provide tools to educators to develop their own AR content without requiring a technical background. Though some educators previously reported that due to their non-technical backgrounds or time constraints, there is no reason that developing a lesson for a physics course should expect an educator to be a software engineer. Providing tools that constrain the problem to a specific domain, such as problem banks or widgets that can be merged into a cohesive illustration would be helpful for those educators.

One idea floated by one of the educators interviewed during the retrospective sessions after Study 3 stated that the creation of a community-driven, PhET-like experience repository would be a good course of action for ensuring adoption. This would be an excellent course of action to assist those educators who are already expected to carry out many tasks in their day-to-day classroom operations. The review process and design guidelines[1] of PhET are available publicly and could be easily adapted to 3D content for an AR application.

The COVID-19 Pandemic

The work for the final study was completed in 2020, a year which was marred by the COVID-19 pandemic. The pandemic forced students to shift to remote learning and heavily delayed the schedule for completion of the study. We believe that there were unintended consequences of the new experience students were faced with. During these times, most people in the United States were required to socially distance themselves from other individuals from outside their own households. Schools being closed meant there were limited opportunities for in-person, collaborative learning experiences. One difference we noted related to feedback collected about students' preferred use cases. The feedback from Study 2 specified that there was a trend towards favoring using AR figures for all parts of a physics lesson and in person lab. However, the results of Study 3 emphasized that physical labs without AR elements were still necessary, with many students specifically

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[1] For information regarding this process, see: `https://phet.colorado.edu/publications/phet_design_process.pdf`

stating that they recognize that they prefer in-person learning and working with physical tools in collaborative, in-person labs. Because of this dramatic shift in feedback, we can conclude that either there was a sampling bias between Study 2 and Study 3 that was not inherently discernible from the demographics of the two study populations, or there was a shift in general opinions of remote learning and a desire to return to in-person coursework. This distinction is also present in the retrospective provided by the educators.

As an aside, this dissertation originally was conceived as ”Physics in the Living Room,” the goal of which was to enable remote learners to experience similar labs to in-person learners using augmented reality labs in their own living spaces. It is interesting to think about how opinions have shifted based on nearly a year of being disallowed the privilege to participate in standard in-person labs. Perhaps that original idea would have been well-received given the way educators were forced to pivot to remote learning out of necessity. Having a tool in place which can still provide a tangible learning experience with integration with the real world will remain a useful tool, especially if another, similar pandemic or distancing event occurs.

CHAPTER 7: CONCLUSION AND FUTURE WORK

Augmented reality will continue to stall in adoption without more inroads into domains that encourage innovation. We continue to point towards education as the area that would most benefit from new techniques for information presentation. Based on these, we can infer that education is an excellent use case for AR, especially for topics like physics that have clear spatial relationships between real world objects. AR headsets enable various new methods of presenting these relationships, but choosing which methods to use is a question that needs answering. Do we want students to interact with real or virtual objects? Do we want the real world to influence what information is being presented, or do we want a controlled virtual environment?

Over the course of this dissertation, we have presented the development of three iteratively designed prototypes and the results of three corresponding user studies. The first of these user studies explored the opinions of physics educators and their perceived application capability needs. Specifically, they detailed how AR would be used in their courses, how students would use the devices during laboratories, how teachers would use them during lectures, and how AR experiences could be used as tools for reinforcement of concepts for students who might be suffering from poor performance in specific topics. Educators were of the opinion that if the applications were sufficiently well-made, they would be able to use them in their courses to assist in running labs for ”invisible” concepts like electricity and magnetism, as well as allowing for fine-tuned control over kinematics simulations. Educators hoped that AR would enable distance learners to experience similar laboratories to students who participated in traditional in person labs.

In the second study, students were polled for their opinions on how they liked AR as a tool for their own learning. Participants in the study were asked about their experiences with other types of learning software and how they felt a rather simple visualization of a physics concept helped them to understand the concept itself. Students generally were excited about the capabilities that they inferred the Hololens had and wanted to see how much a more mature application would benefit them in their courses. Many students felt that the device was sufficient but sometimes detrimental to their performance and experience, but they also reported that they enjoyed the content presented and felt with more polish, it could be used in their courses.

The third and last study presented in this paper is a comparison between the third version of the AR Physics application we developed, dubbed PhyAR2, and a VR version of the same application. We expected that the AR display would provide a better sense of connection with the real world but would not perform better from an educational perspective. Based on the results of the study, there is a slight degree of agreement with that idea. We therefore conclude that while VR might have a lower barrier to entry than AR, it might be better in certain settings which we did not evaluate, but we leave those questions to future work. Students showed themselves to benefit from electricity and magnetism education with regard to their performance with less visible problems.

Future Work

We have conceived four additional directions for this research which we believe would assist in better understanding use cases for AR in the classroom.

Longitudinal Study comparing AR, VR, and Supplemental Instruction

The key to determining if there is truly a benefit to using applications like PhyAR in courses is to use it in a real course and compare against a baseline of a traditional class. We would like to present a subset of a course an AR version of the same lectures and labs as a traditional course and determine learning effects by measuring differences in recall and test performance. To design this study, we would draw inspiration from the studies conducted by Cai et al. in studies conducted with a sample of high school students [17, 18]. We would recruit a sample of college students taking Physics II (Electricity and Magnetism) to determine if using AR and VR applications within their physics courses was beneficial to their learning results and conceptions of learning. The study design would be between subjects. The concept of emphasis for the study would likely be magnetism and magnetic flux, as there is enough content to cover multiple weeks of a semester to ensure proper recall. We conceive that there would be four conditions for this study:

- **Control** - Students experience a traditional in person lecture and physical labs associated with the lecture.
- **SI Lecture** - Students experience a traditional in person lecture, a supplemental instruction laboratory conducted by a teachers assistant which reviews the lecture prior to students being presented with the physical lab, and physical labs associated with the lecture.
- **AR Reinforcement** - Students experience a traditional in person lecture, a supplemental instruction session with AR devices provided to students as reinforcement, and physical labs associated with the lecture.
- **VR Reinforcement** - Students experience a traditional in person lecture, a supplemental instruction session with VR devices provided to students as reinforcement, and physical labs associated with the lecture.

The dependent variables would be a set of validated aptitude tests measuring learning results and a set of questionnaires asking about students experience with the course. We hypothesize that students would find the AR reinforcement and VR reinforcement conditions more motivating. We also hypothesize that the SI Lecture, AR Reinforcement and VR Reinforcement will all have superior learning effects of the Control group due to the presence of an additional reinforcement session.

Exploratory Study with Improved Hardware

We would like to migrate the applications to the Hololens 2 and leverage the added hand tracking options to enable a table-top scenario instead of the standing content that was used in the last two studies we conducted. This would serve to alleviate problems with the field of view of the devices and improve the interaction capabilities, which were two of the largest shortcomings mentioned during studies 2 and 3. Specifically, we would emphasize a tabletop study similar to the one conducted by Villanueva et al. [69], who leveraged AR in a tabletop setting with markers on relevant elements to provide annotation to the user. The demonstration about Faraday's law and electromagnetic flux would be used in this configuration, with multiple, marker tracked objects used to provide additional visualization of fields on top of the physical objects. The tracked objects we would use would be magnets of different strengths and shapes, a coil for induction, and a voltmeter. The visualization provided in the AR headset would be field lines and annotations. To conduct the study, students would be recruited from college physics courses and asked to complete a laboratory experiment and then provide feedback about their understanding of a concept and their experience completing the laboratory. The study design would be between subjects. The two conditions we conceive for this experiment would be a control using a traditional lab notebook and physical measuring devices, and an AR condition using a lab notebook, marker tracked objects, and AR annotations provided to the user with further explanation. Participants would experience only one of these two conditions. Our expectation is that participants would find the AR condition more motivating and have better learning results.

Exploring Forces and Momentum in Elastic and Inelastic Collisions

An early lab conducted during the course of Physics I at the University of Central Florida is an exploration of collision between sleds on a fixed, one-dimensional rail. Students are tasked with placing sleds of various weights on the rail and causing them to collide in different ways, and then recording their expectations and measuring the real effects. We would like to enable this lab to be augmented via an AR headset to include real-time visualization of forces, force diagrams, logged information about the sleds at various time-steps. To enable these features, we would instrument each sled with a fixed colored marker or implement object tracking on each sled so that they can be tracked multiple times per second. Physical properties of the sleds would be known to the application so that forces and graphs could be correctly presented to the learner. This tool would be compared against a traditional physical lab without any augmented information presentation. The study design would be between subjects.

Tactile Feedback in VR

Based on the idea that the best part of Study 3's AR condition was the tactile feedback enabled by the real world objects, we would like to explore if using a haptic glove in a VR scene with content about magnetic fields would be as beneficial to learning effects as a traditional lecture and exploratory lab. The magnetic field could provide feedback based on the strength of the field around magnets in the scene. This would be in addition to presenting a lecture within the virtual environment. To conduct a study evaluating this application, we would compare against a control textbook chapter with traditional static 2D figures and a short lab. Participants would be recruited from a local universities Physics II course. Dependent variables would be participant qualitative feedback about their experience and responses to validated aptitude tests.

“Fill in the Blank”

One missing element from all studies run during this dissertation was an investigation-based lesson which required students to answer questions using the presented information. One example of this would be replicating a specific electrical field by placing point charges of the appropriate strength at specific points in space. This ”Fill-in-the-Blank” paradigm encourages students to better demonstrate their understanding of concepts than a multiple choice questionnaire. To evaluate the classroom utility of such a tool, a study would be conducted in which this AR-based ”Fill-in-the-Blank” testing application would be presented to students have they have experienced a lecture about the concepts. Students would also be presented with a traditional, multiple choice with free response test to compare to as a baseline. This study would be within-subjects design using a population of students recruited from a local high school or college. Dependent variables collected from the study would be student test scores on the traditional tests, their scores on the AR ”Fill-in-the-Blank” application, and feedback collected from the proctoring educator, who would record their observations of the students behaviors during the tests. We hypothesize that students will experience less frustration with the ”Fill-in-the-Blank” application because there is an interactive visualization which can help to guide them to the answer more so than a traditional pen-and-paper test would.

APPENDIX A: IRB APPROVAL OF HOLOPHYSICS STUDY

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Corey Pittman**
Date: **October 30, 2018**

Dear Researcher:

On 10/30/2018 the IRB approved the following human participant research until 10/29/2019 inclusive:

Type of Review:	UCF Initial Review Submission Form Expedited Review
Project Title:	A Requirements Analysis of Augmented Reality Physics Applications for Secondary and Post-secondary Education
Investigator:	Corey Pittman
IRB Number:	SBE-18-14473
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 10/29/2019, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

This letter is signed by:

Signature applied by Jessica Jacques on 10/30/2018 04:11:49 PM EDT

Designated Reviewer

APPENDIX B: IRB APPROVAL OF PHYAR 1 AND 2 STUDY

UNIVERSITY OF CENTRAL FLORIDA

Institutional Review Board
FWA00000351
IRB00001138Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

APPROVAL

October 31, 2019

Dear Corey Pittman:

On 10/31/2019, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title:	Collecting student perspective of AR application for physics education
Investigator:	Corey Pittman
IRB ID:	STUDY00001053
Funding:	None
Grant ID:	None
IND, IDE, or HDE:	None
Documents Reviewed:	• Bounce Image, Category: Other; • Consent Document, Category: Consent Form; • Demographics/Pre-Questionaire, Category: Survey / Questionnaire; • Doppler Effect Image, Category: Other; • Electric Field Image, Category: Other; • IRB Protocol, Category: IRB Protocol; • Light Switch Image, Category: Other; • Magnets Image, Category: Other; • Post-Questionnaire, Category: Survey / Questionnaire; • Ramp Image, Category: Other; • Recruitment Email, Category: Recruitment Materials;

The IRB approved the protocol from 10/31/2019.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Adrienne Showman
Designated Reviewer

APPENDIX C: DEMOGRAPHICS SURVEY OF PHYAR 1 STUDY

Demographics Survey Participant: _______

Age: ___________________

Gender: ___________________

Education Level: _________________

Major: ___________________

Do you wear glasses or contacts?

Yes No

Are you required to take Physics I?

Yes, with Calculus *Yes, without Calculus* *Yes, unsure* *No*

Have you taken Physics I? (Mechanics, Thermodynamics, Fluids)

Yes *No* *Currently Enrolled*

If you answered yes, did you consider the subject difficult or easy?

Difficult *Somewhat Difficult* *Neutral* *Somewhat Easy* *Easy*

Are you required to take Physics II?

Yes, with Calculus *Yes, without Calculus* *Yes, unsure* *No*

Have you taken Physics II? (Electricity, Magnetism, Optics)

Yes *No* *Currently Enrolled*

If you answered yes, did you consider the subjects difficult?

Difficult *Somewhat Difficult* *Neutral* *Somewhat Easy* *Easy*

How often do you play video games?

Never *Rarely* *Sometimes* *Frequently* *Always*

Have you ever used a Virtual Reality headset? (Oculus Rift/PSVR/HTC Vive)

Yes *No*

How you ever used an Augmented Reality headset? (Magic Leap/Microsoft Hololens/Meta)

Yes *No*

APPENDIX D: POST-STUDY QUESTIONNAIRE OF PHYAR 1 STUDY

Post-Study Questionnaire Participant: _______

In the following section, circle the response that best describes the degree to which you agree with the statement.

This AR application is easy to use.

Strongly Disagree Disagree Neutral Agree Strongly Agree

The content of the AR application was easy to understand.

Strongly Disagree Disagree Neutral Agree Strongly Agree

I learned more from the AR application’s presentation of information than from my lab sessions.

Strongly Disagree Disagree Neutral Agree Strongly Agree

I learned more from the AR application’s presentation of information than from my lectures.

Strongly Disagree Disagree Neutral Agree Strongly Agree

The application was more instructive than a textbook.

Strongly Disagree Disagree Neutral Agree Strongly Agree

The experience of using an AR headset made me want to continue using the application.

Strongly Disagree Disagree Neutral Agree Strongly Agree

I found the AR application exciting.

Strongly Disagree Disagree Neutral Agree Strongly Agree

I found the AR application motivating.

Strongly Disagree Disagree Neutral Agree Strongly Agree

I found the AR application interesting.

Strongly Disagree Disagree Neutral Agree Strongly Agree

I would be able to thoroughly learn a subject from a more complete AR application.

Strongly Disagree Disagree Neutral Agree Strongly Agree

This AR application’s capabilities meet my requirements

Strongly Disagree Disagree Neutral Agree Strongly Agree

Post-Study Questionnaire Participant: _______

A lecture presented by a teacher using a similar headset and presenting a live video feed would be beneficial to my understanding of a new concept.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Collaborating with other students in a group lab while using AR headsets would be beneficial.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Do you have any experience with education software (PC, Tablet, VR/AR)?

Yes No

If you answered yes to the previous question, please list and briefly describe the education software you used:

Describe what you like about the AR physics applications.

Describe what you dislike about the AR physics applications.

Post-Study Questionnaire Participant: _______

In what settings would you want to use this type of AR application? Why? (Circle all that apply)

Individual Study *Collaborative Projects* *Instructor Demonstration*

Other:

In what way(s) do you believe this type of application could be used in a physics class?

If you had a choice between a physical lab experiment and an AR lab experiment, which would you prefer and why?

In what way(s) could the application be improved.

Additional comments:

APPENDIX E: DEMOGRAPHICS SURVEY OF PHYAR 2 STUDY

Demographics Survey Participant: _______

Age: ___________________

Gender: ___________________

Education Level: _________________

Major: ___________________

Do you wear glasses or contacts?

Yes No

Are you required to take Physics I?

Yes, with Calculus *Yes, without Calculus* *Yes, unsure* *No*

Have you taken Physics I? (Mechanics, Thermodynamics, Fluids)

Yes *No* *Currently Enrolled*

If you answered yes, did you consider the subject difficult or easy?

Difficult *Somewhat Difficult* *Neutral* *Somewhat Easy* *Easy*

Are you required to take Physics II?

Yes, with Calculus *Yes, without Calculus* *Yes, unsure* *No*

Have you taken Physics II? (Electricity, Magnetism, Optics)

Yes *No* *Currently Enrolled*

If you answered yes, did you consider the subjects difficult?

Difficult *Somewhat Difficult* *Neutral* *Somewhat Easy* *Easy*

How often do you play video games?

Never *Rarely* *Sometimes* *Frequently* *Always*

Have you ever used a Virtual Reality headset? (Oculus Rift/PSVR/HTC Vive)

Yes *No*

How you ever used an Augmented Reality headset? (Magic Leap/Microsoft Hololens/Meta)

Yes *No*

APPENDIX F: POST-CONDITION QUESTIONNAIRE OF PHYAR 2 STUDY

Post-Condition Questionnaire Participant: _______

Experience Order:	1	2
Headset:	AR	VR
Concept:	Coulomb’s	Faraday’s

In the following section, circle the response that best describes the degree to which you agree with the statement.

This AR/VR application is easy to use.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

The content of the AR/VR application was easy to understand.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I learned more from the AR/VR application’s presentation of information than from my lab sessions.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I learned more from the AR/VR application’s presentation of information than from my lectures.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

The application was more instructive than a textbook.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

The experience of using an AR/VR headset made me want to continue using the application.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I found the AR/VR application exciting.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I found the AR/VR application motivating.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I found the AR/VR application interesting.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I would be able to thoroughly learn a subject from a more complete AR/VR application.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Post-Condition Questionnaire Participant: _______

This AR/VR application’s capabilities meet my requirements

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

A lecture presented by a teacher using a similar headset and presenting a live video feed would be beneficial to my understanding of a new concept.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Collaborating with other students in a group lab while using AR/VR headsets would be beneficial.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Do you have any experience with education software (PC, Tablet, VR/AR)?

Yes No

If you answered yes to the previous question, please list and briefly describe the education software you used:

Describe what you like about the AR/VR physics application.

Describe what you dislike about the AR/VR physics application.

Post-Condition Questionnaire Participant: _______

In what settings would you want to use this type of application? Why? (Circle all that apply)

Individual Study *Collaborative Projects* *Instructor Demonstration*

Other:

In what way(s) do you believe this type of application could be used in a physics class?

If you had a choice between a physical lab experiment and an AR/VR lab experiment, which would you prefer and why?

In what way(s) could the application be improved.

Additional comments:

APPENDIX G: POST-STUDY QUESTIONNAIRE OF PHYAR 2 STUDY

Post-Study Questionnaire Participant: _______

In the following section, circle the response that best describes the degree to which you agree with the statement.

This AR application is easy to use.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

The content of the AR application was easy to understand.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I learned more from the AR application’s presentation of information than from my lab sessions.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I learned more from the AR application’s presentation of information than from my lectures.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

The application was more instructive than a textbook.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

The experience of using an AR headset made me want to continue using the application.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I found the AR application exciting.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I found the AR application motivating.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I found the AR application interesting.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

I would be able to thoroughly learn a subject from a more complete AR application.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

This AR application’s capabilities meet my requirements

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Post-Study Questionnaire Participant: _______

A lecture presented by a teacher using a similar headset and presenting a live video feed would be beneficial to my understanding of a new concept.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Collaborating with other students in a group lab while using AR headsets would be beneficial.

Strongly Disagree *Disagree* *Neutral* *Agree* *Strongly Agree*

Do you have any experience with education software (PC, Tablet, VR/AR)?

Yes No

If you answered yes to the previous question, please list and briefly describe the education software you used:

Describe what you like about the AR physics applications.

Describe what you dislike about the AR physics applications.

Post-Study Questionnaire Participant: _______

In what settings would you want to use this type of AR application? Why? (Circle all that apply)

Individual Study *Collaborative Projects* *Instructor Demonstration*

Other:

In what way(s) do you believe this type of application could be used in a physics class?

If you had a choice between a physical lab experiment and an AR lab experiment, which would you prefer and why?

In what way(s) could the application be improved.

Additional comments:

APPENDIX H: APTITUDE TEST FOR COULOMB'S LAW FROM PHYAR 2 STUDY

Coulomb’s Law Aptitude Test

1. Find the magnitude of the force between two charges of 1.0 C each which are 1.0 meter apart?
    a. 9E-9 N
    b. 9E9 N
    c. 1.1E10 N
    d. 1.1E-10 N

2. Calculate the force exerted between two charged objects separated by a distance of 0.6 m. One object has a charge of -5 C and the other has a charge of +2.0 C.
    a. -1.5E-11 N
    b. 2.5E-11 N
    c. -2.5E11 N
    d. -7.5E-10 N

3. If each of the charges doubles, what happens to the force?
    a. Quadruples
    b. Doubles
    c. Stays the same
    d. Reduced by half

4. If the distance doubles, what happens to the force?
    a. Reduced by half
    b. Reduced by ¼
    c. Stays the same
    d. Quadruples

5. If the distance is reduced by half, what happens to the force?
    a. Quadruples
    b. Doubles
    c. Triples
    d. Reduces by half

6. Electrostatic force F is directly proportional to:
    a. R^2
    b. Q1
    c. Q2
    d. Both q1 and q2

7. When distance increases, electrostatic force __________; we call this relationship ____________ proportional
    a. Decreases; directly
    b. Decreases; inversely
    c. Increases; inversely
    d. Increases; directly

8. What happens to the force between two charged objects if you reduce the distance between two objects from 30 cm to 10 cm?
    a. 1/3x
    b. 20x
    c. 3x
    d. 9x

9. What happens to the force between two charged objects if you double the distance between them and double the magnitude of one charge?
    a. 4x
    b. 6x
    c. 1/2x
    d. 1/6x

10. What happens to the force between two charged objects when you triple the magnitude of both charges?
    a. 3x
    b. 6x
    c. 9x
    d. 1/6x

$$F = k\frac{q_1 q_2}{r^2}$$

F = electric force
k = Coulomb constant
q_1, q_2 = charges
r = distance of separation

APPENDIX I: APTITUDE TEST FOR FARADAY'S LAW FROM PHYAR 2 STUDY

Faraday's Law/Lenz's Law Aptitude Test

1. Can you see magnetic fields?
   a. Yes
   b. No
2. Magnetic poles that are unlike ________and magnetic poles that are alike ___________.
   a. Run; stay
   b. Stay; repel
   c. Attract; repel
   d. Repel; attract
3. Why does a compass needle point north?
   a. Because it is attracted to the Magnetic North Pole
   b. Because it is attracted to the Magnetic South
   c. Because North is Up
   d. Because North is Down

4. _______ Law says that the Induced current is proportional to the change of magnetic flux
   a. Lenz's
   b. Faraday's
   c. Ampere's

5. The unit of magnetic flux is the:
   a. Henry
   b. Tesla
   c. Faraday
   d. Weber
6. What is a Magnetic Field?
   a. A measurement of the total magnetic field which passes through a given area
   b. A region around a magnet where a magnetic force can be experienced
   c. A region around a charged particle or object within which a force would be exerted on other charged particles or objects
   d. The magnetic flux per unit area around an area at right angles to the magnetic field

7. Faraday's Law states that the induced emf is proportional to the:
   a. current
   b. cross-sectional area of the coil
   c. rate of change in the flux of the coil

8. If a magnet is pushed into a coil, voltage is induced across the coil. If the same magnet is pushed into a coil with twice the number of loops:
   a. One half as much voltage is induced
   b. The same voltage is induced
   c. Twice as much voltage is induced
   d. Four time as much voltage is induced

9. Electromagnetic induction is defined as a change in _____.
    a. Surface area
    b. Magnetic flux
    c. Magnetic poles
    d. Current
10. Faraday's law states that $\epsilon = -N\frac{\Delta\emptyset}{\Delta t}$, what is the physical meaning of the equation?
    a. The induced emf is proportional to the rate of change of magnetic flux
    b. The magnetic field direction is proportional to the current of loop
    c. The current of circuit is proportional to the voltage applied in the circuit
    d. The induced emf is not equal to change of magnetic field

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