Challenges of Using Augmented Reality to Teach Magnetic Field Concepts and Representations

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Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
under the Executive Committee
of the Graduate School of the Arts and Sciences

COLUMBIA UNIVERSITY

2022

Abstract

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Many efforts to reform science educational standards and structure have placed an emphasis on directing learners to communicate about concepts using external representations (ERs). Techniques to develop competencies with ERs often ask learners to develop understanding outside of a physical context while concurrently making connections back to the context—a very challenging task that often results in incomplete learning.

This dissertation work is presented in part as a journal article and presents a study that compared the effectiveness of a computer simulation to an augmented reality (AR) simulation for developing magnetic field conceptual and representational knowledge. The AR technology provides a feature called a dynamic overlay that can present ERs in a real-world context. The study was done with six classes of ninth grade physics students and evaluated learning, proficiency of exploration, and intrinsic motivation to engage with the activity and technology. Results from this study show that contrary to expectations, students who used AR performed similarly to students who used the computer simulation conceptual and representational knowledge assessment. However, students who engaged with AR demonstrated worse exploration on average and had lower levels of intrinsic motivation. These outcomes provide evidence to the difficulty of using AR for teaching the ERs of challenging concepts and the complexities of implementing novel technologies into a standard classroom environment.

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Acknowledgements

I would like to thank my committee members and my family for supporting me through this process. A special thanks to Dr. Cathy Chase who has been with me through many ups and downs of my journey through my doctoral program and provided amazing feedback and support when I needed it most. A special thanks also to Dr. Colleen Megowan-Romanowicz who took on a role of my advisor on her own accord and provided support in ways I cannot every appreciate enough.

Thanks to all of my students and fellow faculty members that helped me to make this possible and collect data. Without you I would never have been able to collect the data I needed. Thanks to my parents, Sai and Sudha Kumar who provided me with confidence, presence, and a deep love for science that helped me make it through.

Finally, a special thanks to Richelle, my wife, and Onyx, my dog, who have put up with my anger and frustration on a daily basis and supported me at some of my lowest points. I love you both.

Chapter 1: Theoretical Frame

Complex scientific phenomena are often explained and communicated via external representations, or ERs (Kirch, 2010; Kirsh, 2009), and there is clear evidence that experts use ERs to guide their own problem solving and understanding (Gooding, 2010; Kozma & Russell, 1997; L. Martin & Schwartz, 2009). The main purpose of ERs is to provide visualizations of real-world phenomena, often combining static features, dynamic processes, and multiple visual scales. Unfortunately, external representations are often isolated from the concrete, physical situations they refer to (Atilola et al., 2014; Rosengrant et al., 2005), a problem that is reinforced by instructional methods and technology that do not bridge that distance directly. Regardless of the instructional method, learners often have difficulty identifying the ER-phenomenon connection (Rosengrant et al., 2009) and frequently misrepresent or misunderstand the central concepts (Scherr & Redish, 2005). Instructional designers and researchers have tried various approaches including modeling instruction (Wells et al., 1995), model-based reasoning (Nersessian, 1999), and adaptive feedback technologies (Rau, 2013); however, the ER-physical connection remains obscure.

The present work aims to explore the potential of augmented reality (AR) as a novel method to teach about ERs in a particularly challenging domain, magnetic fields. Often solely taught through virtual simulations or brief physical interactions (bar magnets, iron filings, and compasses), learners still exhibit challenges with understanding the varied relevant ERs (Campos et al., 2021; Fatmaryanti et al., 2019; Guth & Pegg, 1994). AR can spatially combine virtual representations with a physical object or scenario, known as a dynamic spatial overlay providing a different way of interacting with magnetic fields.

1.1 Representational Competence in Science

The term “representation” refers to two distinct, yet related ideas - internal representations and external representations. Internal representations are knowledge structures or mental models within an individual’s mind (Zhang, 1997), while external representations, or ERs, are physical objects or images that exist outside the mind and hold knowledge and rules about physical phenomena (Palmer, 1977; Zhang, 1997). ERs, like diagrams, images, graphs, and equations, often exist as part of a network and work together to fully encompass the intricacies of a phenomena (Opfermann et al., 2017; Wu & Puntambekar, 2012). ERs can provide descriptions, act as a reference image, or showcase analytical data about a physical situation. Researchers have found that ERs are used for many purposes across science domains such as biology (Tsui & Treagust, 2013), chemistry (Kozma & Russell, 2005; Stull et al., 2016) and physics (Kohl & Finkelstein, 2008).

Given the centrality of ERs in learning and doing science, instructional designers focus on designing methods to acquire *representational competence*, or RC skills. RC is generally defined as the ability to create ERs from conceptual knowledge, decode the conceptual knowledge from an ER, communicate with ERs, and use ERs to solve problems of the domain (Ainsworth, 2006; Airey & Linder, 2009; Kozma & Russell, 2005). The development of these skills relies on instruction that gives learners opportunities to clearly see and reflect on the connections between the physical phenomenon and conceptually relevant ERs (Rau & Matthews, 2017; Stieff et al., 2011; Stull et al., 2016) and create and revise ERs to work towards a concrete understanding (Hubber et al., 2010; Krajcik & Merritt, 2012). While most research in this area seeks to influence RC skills in a widespread way, no instructional method can successfully provide blanketed effects. A main focus of this work is to provide a focus on only two RC skills: creation and interpretation of ERs.

Even with well-developed instruction, learners struggle to see a strong connection between ERs and the phenomenon they represent. This difficulty to connect the ER and phenomenon arises from two factors. First, these images and captions often prioritize clarity and simplicity, but sacrifice saliency of the ER-phenomenon connection. In some cases, this connection is presented as a verbal description or highly-stylized diagram (Ainsworth & Peevers, 2003; Rau, 2015; Rau et al., 2015), potentially causing problems with connecting the ER to the physical world (Nokes-Malach & Mestre, 2013) and transferring the ER to novel situations (Rappoport & Ashkenazi, 2008). Second, the physical world is dynamic, changing with time and space, a feature that cannot be adequately captured with static text or images. While animations and videos can provide some dynamism, these methods suffer from relying again on simplistic ERs of the concepts. Research shows that natural physical experiences can be a potential solution by helping to integrate the ER with sensory information allowing for better interpretation of the ERs (Han & Black, 2011; T. Martin & Schwartz, 2005) and aid in constructing mental simulations when recalling the ER (Barsalou, 2008; Jang et al., 2017). This is reasonable as ERs are meant to be used in context to solve problems, communicate ideas, and constrain interpretation (Ainsworth, 2006; Kirsh, 2010). Researchers have found benefits to combining virtual and physical information for both scientific conceptual and procedural understanding, (Blikstein et al., 2012; Gire et al., 2010; Olympiou & Zacharia, 2012); however, underlying aspects of natural physical contexts are often invisible and contain extraneous factors that mask the central concepts and lead to incomplete understanding of ERs and restrict learners' ability to transfer (Schwartz & Martin, 2006).

1.2 A Proposal: Augmented Reality

This work proposes to use an immersive technology that integrates the physical and virtual world and influence the development of RC skills: augmented reality or AR. AR sits on a spectrum of immersive technologies that aim to integrate the physical and virtual world with a higher emphasis on real world presence (Azuma, 1997; Milgram et al., 1995). Some commercial applications of AR can be seen in Figure 1; however, AR can also be

Figure 1

Example of Augmented Reality Applications

used for educational implementations like environmental instruction (Grotzer et al., 2015; Kerawalla et al., 2006), augmented books (Akçayir et al., 2016; Billinghurst, 2002; Hornecker & Dünser, 2009) or real-world vocabulary learning (Santos et al., 2016). AR uses a technological feature known as a dynamic spatial overlay where virtual images are presented in the physical world. Figure 2 provides a good example of this overlay feature: a GPS program. Instead of providing a text list or guided directions, the overlay shows the directions superimposed upon the physical world. As the user drives, the information shown to them will change accordingly in the space that is easy and relevant to the task at-hand. For example, as the turn approaches, the street name and instructions on the top right will change along with the estimated time of arrival (ETA) and time left on the drive on the top left.

The dynamic spatial overlay simultaneously combines three features that connect virtual representations with the physical world: *natural interactions, spatial integration,* and *dynamic connections*. First, the spatial overlay encourages individuals to use natural or everyday

Figure 2

Example of the dynamic spatial overlay of GPS while driving a car.

interactions to explore the physical and virtual world. Second, the overlay superimposes virtual information spatially atop the physical world, allowing learners to formulate connections between the two. Finally, the overlay creates a link where changes in the physical world manifest as dynamic changes to the virtual information.

The interaction of knowledge and context is especially important to the use of ERs and the exercising of RC skills, such as communication of central ideas within a context (Airey & Linder, 2009; Fredlund et al., 2014; Kirch, 2010). Instruction using tangible objects create opportunities for a learning experience that is grounded in real-world action that can be called upon when needed (Kontra et al., 2015), unlike solely virtual systems (Hofstein & Lunetta, 2003). This grounding experience situates the content within a natural interaction, allowing learners to rely on their prior everyday actions (J. S. Brown et al., 1989; Bujak et al., 2013) and creating opportunities for embodied experience where their physical action has ties to the abstract ideas (Black et al., 2012; Lindgren & Johnson-Glenberg, 2013). Many researchers have tried combining the two to exploit the positive features of each through sequential combination yielding positive results for learning (Blikstein et al., 2012; Gire et al., 2010; Olympiou & Zacharia, 2012; Suh & Moyer, 2007; Toth et al., 2009).

The potential for the spatial overlay is supported by grounded and situated cognition. The reliance on the physical world can help to restrict interpretation of ERs (Greeno, 1997; Klahr & Dunbar, 1988), manipulate complex ideas around ERs (T. Martin & Schwartz, 2005; Pande & Chandrasekharan, 2017), and connect ERs to everyday experiences (Barsalou, 2008; Pouw et al., 2014). Through exploration and interaction with the content and environment, learners can exercise their natural exploratory behavior and see invisible factors at play without becoming too tied to a particular environment, a productive strategy for encouraging learning and transfer (Pouw, van Gog & Paas, 2014).

Yoon et al. (2017) provide an example of how the dynamic spatial overlay can be used for teaching a challenging topic, Bernoulli's principle. Their implementation used this spatial placement feature to display digital air flow around a floating ball. The students could use natural interactions with the ball and air in both conditions but were only able to see the superimposed air pressure lines causing the floating behavior through the overlay. The researchers found that the students who used the overlay were better able to connect the air flow representation to the physical phenomenon than students that did not use the overlay. Other example overlays allow students to see changes in magnetic field lines as they manipulate physical magnets (Matsutomo et al., 2012), see relevant vocabulary as they focus on objects around a room (Hsu, 2017), or see titration reactions for a chemistry lab (Tee et al., 2018).

If the overlay were to stop here, it would not do justice to the *dynamic* nature of scientific phenomenon—the fact that real changes affect the representational structure. Luckily, the spatial overlay also creates a dynamic link between the real world and the virtual ER. Current dynamic displays focus on integration of changes across multiple ERs, but often not in conjunction with spatial or real-world integration (Ainsworth & VanLabeke, 2004; Huk, 2006; Mayer & Sims, 1994; Schnotz & Bannert, 2003; van der Meij & de Jong, 2006). In this sense, *spatial* refers to a physical overlapping of the ERs and *real-world* refers to combining the ER with real-world tangible objects. By relying exclusively on presenting information via 2D computer screens and virtual images, dynamic displays are doing an injustice to the content by remaining disconnected from the world—ERs are meant to be representations of events from the real world. The dynamic spatial overlay will provide the *spatial* and *natural* affordances of interacting with objects in the physical world but add on the ability to see the *dynamic* changes occurring at the invisible and abstract levels. The virtual representation assists in focusing the learners and seeing the invisible, while the physical experience provides real-world meaning and sensory depth to an otherwise obtuse representation.

1.2.1 Learning with Augmented Reality

While most current research in AR focuses on usability, an increase in accessibility for researchers and content developers has led to more exploration of its learning benefits (Cheng & Tsai, 2013; Garzón et al., 2020; Garzón & Acevedo, 2019; Wu et al., 2013). AR has been used to develop spatial skills (Shelton & Hedley, 2004), familiarize learners with scientific concepts (Grotzer et al., 2015; Kerawalla et al., 2006), and expose learners to laboratory processes (Eursch, 2007). Garzón and Acevedo (2019) conducted a comprehensive meta-analysis on the benefits of AR based on 64 studies. They found that AR has a medium effect on learning gains over a wide range of comparison groups and is best employed in informal settings and in higher education.

Although Garzón and colleagues describe substantial evidence for the benefits of using AR, they themselves describe some limitations of their more restrictive inclusion criteria. Studies evaluating AR benefits also find students performed equally well on a knowledge assessment compared to VR or tablet technologies (e.g. Moro et al., 2017) or conditional benefits based on the type of content (K. T. Huang et al., 2019; Radu & Schneider, 2019). For example, Radu and Schneider conducted a single-condition study that used AR to teach about the scientific principles of audio speakers. They found that AR provided benefits in some conceptual areas (magnetic field shape), but not in others (movement and magnetic field). Reviews through the years have shown that implementation of AR for learning may not be straight-forward (Akçayır & Akçayır, 2017; Sırakaya & Alsancak Sırakaya, 2020; Wu et al., 2013). They find that studies show that AR can increasing cognitive load and have variability in usability and effect based on the form of hardware used. These reviews advocate for further investigation in how to better integrate AR in a range of content areas and environments.

The focus of the research I conducted was to use AR technology to teach about magnetic field concepts. Currently, there is not much research in this area, often focusing more on the usability of the technology, rather than its learning effects (Macedo et al., 2014; Mannus et al., 2011; Matsutomo et al., 2012). However, there are a few studies that have investigated the use of

AR for teaching magnetism and these studies also find a more nuanced effect of AR. Cai et al. (2017) conducted a two-condition study comparing the effects of using a full-body AR simulation of magnetic fields to just using physical bar magnets. The researchers found that students who used AR did manage to perform better on a magnetic field conceptual knowledge assessment. However, the researchers did indicate that students learning about magnetic fields had a shallow understanding and may need more direct instruction to establish a better understanding. In another study, Liu et al. (2021) compared using AR to a traditional experiment with physical objects and a touch-screen 3D simulation for developing an understanding of magnetic fields around bar magnets and the Earth. They found that there was a larger growth in conceptual knowledge as measured by an assessment. However, in this study, students had some level of prior knowledge before engaging with the technology. While these few studies do show some benefits for the use of AR for developing magnetic field knowledge, there is still room for more work to provide a better understanding of where and how AR can be best employed.

Combining the needs illustrated in prior research, my work focuses on the link between a single feature of the AR technology, rather than the AR tool as a whole, and the effects of that feature for learning about magnetic fields. I wanted to explore the potential of, the dynamic spatial overlay aspect of AR, for both conceptual and representational learning of magnetic fields. This feature is what allows for a clearer connection between the physical and virtual world that is central to using representations. To address this comparison, I developed a set of non-immersive computer simulations with extremely similar visualizations and interactivity, but without the real-world overlay provided by AR. More on these computer simulations are addressed in Chapter 2.

1.2.2 Motivation and Augmented Reality

Meta-analyses and meta-reviews (Garzón et al., 2020; Garzón & Acevedo, 2019; Radu, 2014) find that motivation for learning is one of AR's biggest advantages. The AR environment provides both a sense of immersion and personal agency (Bujak et al., 2013; Moro et al., 2017) which have been shown to lead to higher levels of motivation and interest (e.g. Cordova & Lepper, 1996; H.-M. Huang & Liaw, 2014; W. Huang et al., 2021).

This work focuses on *intrinsic* motivation, which is a combination of interest, enjoyment, and inherent satisfaction (Ryan & Deci, 2000). Intrinsic motivation is important in STEM activities that investigate abstract, vague, and invisible concepts. Abstraction and complexity are known to contribute to loss of student interest and disengagement, which can hinder performance (Sadoski, 2001). AR has the potential to improve student intrinsic motivation as students who use AR report high levels of enjoyment, interest, and satisfaction (e.g. Akçayir et al., 2016; Cai et al., 2014; Cai et al., 2017; Santos et al., 2016).

Most AR implementations provide opportunities for students to have more control over their instruction, rather than passively learning, and provide the learners with clearer and more temporally and spatially relevant information (Bujak et al., 2013; Ibáñez & Delgado-Kloos, 2018). Both the active role and salient content create potential for students to maintain, or generate, higher levels of interest in content areas. This work uses these features of AR to teach about ERs of magnetic fields—a challenging and invisible concept. The students participate in only a few days of instruction by *creating* ERs and visualizing *invisible* fields in their environment. Understanding how this AR implementation can facilitate intrinsic motivation is very important—when students develop high levels of intrinsic motivation, they are more likely to stay focused when learning new and challenging ideas.

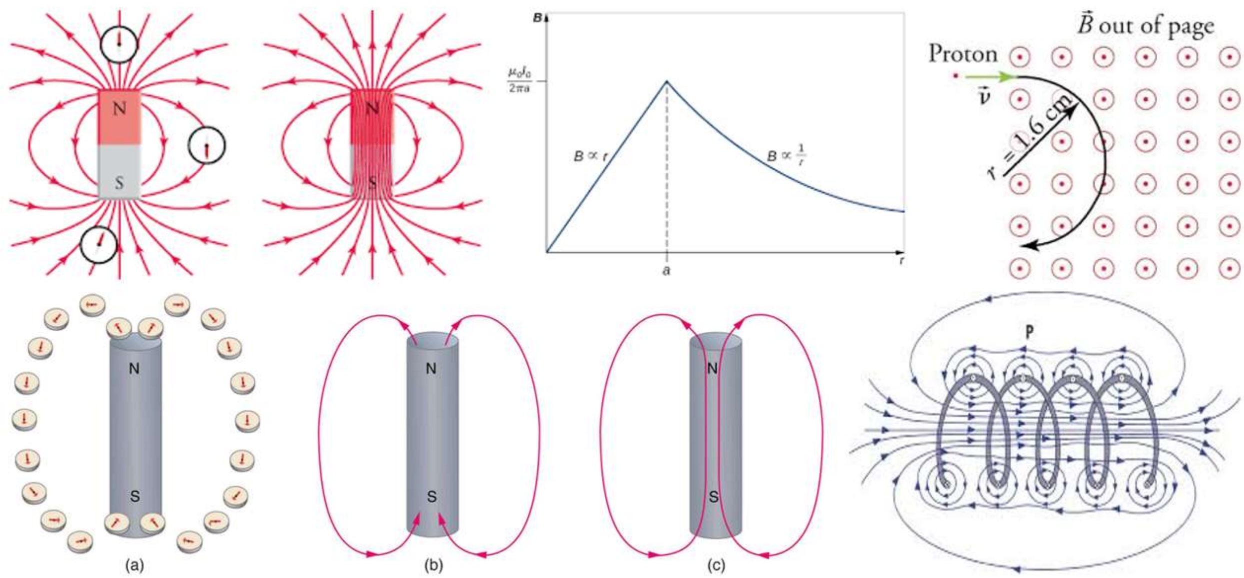
1.3 A Note About Content: Concepts and ERs of Magnetism

This dissertation work specifically focuses on the content area of magnetism. No instructional method or technology should be used in every situation, however the overlay proposed in this work could be a particularly strong tool for science content founded in physical phenomenon with invisible factors. The concepts that surround magnetic behavior exemplify this as individuals are familiar with the effects of magnetic fields and forces but are unable to visualize the underlying causes. This makes the scientific concept of a field a difficult one, as it involves abstract and invisible factors that result in three-dimensional interacting outcomes. Students often have difficulty in understanding the overall concept of a field (Greca & Moreira, 1997) and have varied mental models of how magnetic behavior originates and interacts with other objects (Borges & Gilbert, 1998; Erickson, 1994). In addition, many researchers have found that learners have difficulty understanding the representations of magnetic fields themselves. This often results in learners thinking that field lines really exist (Pocovi & Finley, 2002) or that vectors are depicting trajectories (Törnkvist et al., 1993).

To properly depict the complexity of magnetic fields, scientists have developed a wide range of representations such as equations, graphs, vector diagrams, heat maps, field line diagrams. Some of these are shown in Figure 3. Each ER allows for a different view of how major factors affect the behavior of magnets and objects in a magnetic field; however, few of them include a call to physical experiences and even fewer take account of the three-dimensional nature of the field concept in its entirety. Many instructional experiences stay close to the limitations of these static diagrams, even though learners are meant to understand the physical causes and effects of magnetic behavior. This disconnect between the nature of the ERs, the instructional goals, and the physical manifestation of magnetic fields calls for a reimagining of the manner through which learners are taught these concepts.

Figure 3

Common representations of magnetic fields.



Note: This is a combination of diagrams from OpenStax (2016) and Texas Gateway (2022).

1.4 The Present Work

There are two domains in educational research that have yet had limited connection: external representations in science and augmented reality. Research around ERs has shown that learners find significant challenge in understanding and creating ERs. These ERs are often disconnected from real-world scenarios and phenomena and ultimately learners are unable to transfer their understanding of ERs outside of a highly specific context. Through its dynamic overlay feature, AR is a unique and fairly novel technology that can target this gap by providing immediate connections between an ER and various contexts. While work in AR has shown evidence that using the technology can yield learning benefits, there is not specific analysis on its potential to influence RC skills. This distinction is important as often students can exercise high proficiency when the concepts are presented through one ER and are lost when it is presented in another.

This current work seeks to connect these two domains by evaluating the effects of the dynamic overlay feature of AR on the specific RC skills of decoding and creating ERs within the challenging conceptual area of magnetic fields. The study outlined in this work was an experimental classroom study that asked students to explore magnetic fields around specific objects. Students were asked to interpret and create ERs via their technology and on paper. The effects of the AR technology in this work are compared to a highly similar computer simulation that does not have this overlay feature. This type of highly specific comparison of an AR feature has not yet been done, as creating similar conditions with novel technologies has traditionally been a difficult task.

1.4.1 Research Questions and Hypotheses

This study focuses on four research questions to understand the potential benefits of using the dynamic overlay feature.

RQ1. How do the representations learners create while using a dynamic spatial overlay AR program (AR-D) differ from those created by learners using a computer simulation? This is an exploratory question, as I did not have a strong hypothesis.

RQ2. How do hand-drawn representations created by learners who use AR-D compare to those created by learners who use CompSim?

Hypothesis: Learners using the AR-D program will develop more accurate hand-drawn ERs of magnetic fields during the learning activity than learners using the CompSim because of higher levels of representation integration and more natural interaction behaviors.

RQ3. How do learners who use AR-D perform on an assessment of magnetic field conceptual and representational knowledge compared to those who use the CompSim?

Hypothesis: Learners using the AR-D program will perform better on post-test measures of representational competence of magnetic fields around magnets than those using the CompSim.

RQ4. How does use of the AR-D affect students' intrinsic motivation to use the technology and engage in the magnetic field classroom activity, as compared to use of computer simulations?

Hypothesis: Learners using the AR-D program will have a higher level of intrinsic motivation to engage with their instructional technology and engage in the magnetic field activity.

Chapter 2: Study Design and Methods

2.1 Participants

Participants for this study were 97 high school students from six 9th grade physics classes in a private school in California. Within each class, as the primary researcher, I randomly assigned participating students to use one of the technologies through the activity. The students were all part of a non-accelerated physics class with some prior knowledge of the physical behavior of magnets due to everyday experiences. For most of the students (69%), I was also their physics teacher; however the activities were all self-guided and the students were told that their performance on these activities had no influence on their grades to limit any teacher/researcher influence that could have been present.

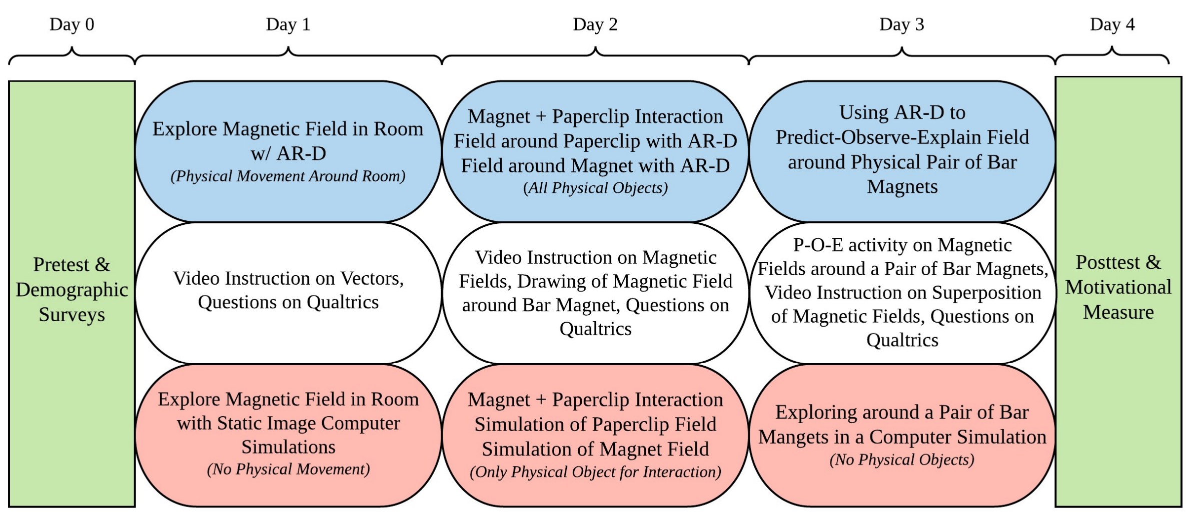
2.2 Study Design and Procedure

The study was a two-condition experimental design comparing the representational and conceptual learning and motivational effects between using AR-D and CompSim technology for learning about magnetic fields. Students were paired up with another student for each day of instruction and were given a new partner to reduce any partner effects. Each pair of students were given one exploration device (either a phone or a computer) during instruction. More detail on this instruction is given in the next section. Figure 4 shows the overall study design.

The major difference between the two groups is based on how they were able to explore the magnetic fields. The AR-D group used a mobile AR tool that the participants can use to create a virtual ER of the magnetic field visually superimposed on the magnets in space. To create these representations, students tapped on the mobile screen to place vectors in the 3D space around them. These vectors were representations of the magnetic field strength at any point and, as the students tapped and moved around, could work together to show the overall magnetic field in their area. Figure 5 shows a possible representation that could be formed by the participants as they explore using the dynamic spatial overlay. While the system itself was dynamic in nature, the magnet was to be stationary allowing the learners to freely explore the field they created from different angles in three dimensions. Essentially, the students were able to use their bodies as tools to explore the magnetic field.

Figure 4

Diagram of study design and intervention sequence.

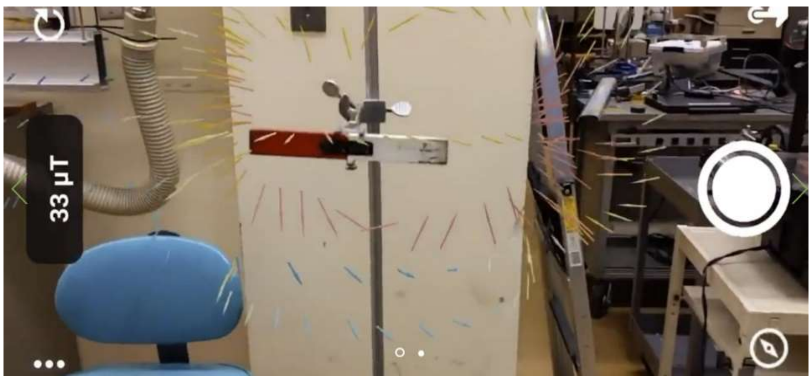


Note: Measures are shown in green, AR-D instruction in blue, CompSim instruction in red.

To best compare the features of the AR-D, I developed a set of computer simulations allow for close parallelism between the two conditions and to provide opportunities to speak to the features of AR-D that are meaningful for learning about the magnetic field concepts. I created a CompSim module that resembled a less immersive version—the visualizations were 2D and the interactions were with mouse and keyboard—of each activity task that students were asked to complete during instruction. In contrast to AR-D, students would interact by using a mouse and clicking on a computer screen to place the arrows that represent the magnetic field while sitting stationary in front of a computer screen. For example, if the students were asked to explore the magnetic field around a paperclip, the AR-D students would use the Magna-AR application to explore the region around a physical paperclip, while the CompSim students would use a mouse and keyboard to explore with a computer simulation that shows a paperclip on the computer screen. Figure 6 show examples of the possible visualizations seen by students for each group. Appendix B provides more information.

Figure 5

Example of field ER created through the AR-D.



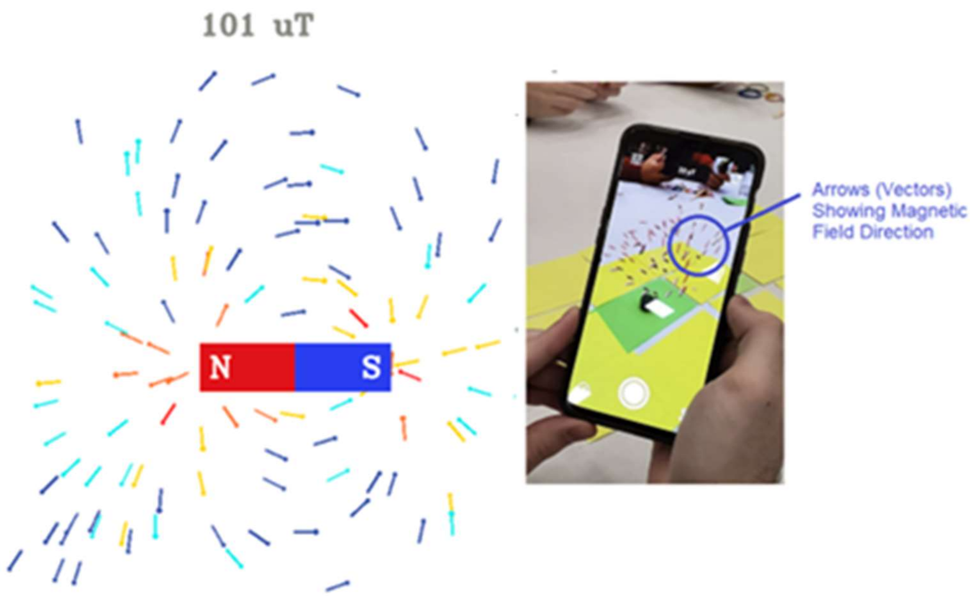
2.2.1 Technology-Assisted Exploration Activity

During the learning activity, participants in the study used either the AR-D or computer simulations to explore the magnetic field in different situations. A set of 8 simulations were created that mirrored activities that the participants were meant to do throughout this study. While the AR-D group did these activities by moving an AR app on a cell phone around physical materials, participants in the CompSim group used computer simulations to engage in similar, yet all-virtual explorations.

In both groups, students were assigned to work with partners as collaborative work has been shown to be successful for AR learning (Garzón et al., 2020). These partners were rotated every day to limit any effects of working with a single partner. Each student was given a worksheet packet on each day that led them to a computer survey that worked in conjunction with the paper packet. All drawings were done on paper, but all written responses were done on the computerized survey. While the students were encouraged to work together for most of the exploration, each student was asked to submit their own drawings and written responses.

Figure 6

Diagram of visualization seen by each group of students.



Students began by exploring the magnetic field in three areas around the room on day 1 and watched a video introduction to vectors to familiarize themselves with their technologies. On day 2, the students watched a short video to clarify the idea of magnetic fields, explored magnetic fields and interactions of a paperclip and magnet and drew a magnetic field representation on paper. On the final day of instruction, I began by giving the AR-D students oly a brief instruction on how to use the technology to explore around the magnets more precisely. I noticed that AR-D students were having some problems doing this on days 1 and 2, and I wanted to provide them with some help so they could see the fields and have more success in the instruction. All the students then explored the magnetic fields associated with three arrangements of a pair of bar magnets through a predict-observe-explain style activity. They were first asked to predict the structure of the magnetic field around three different arrangements of a pair of bar magnets. They were then asked to use their exploration technology (AR-D or CompSim) to explore the magnetic field in these orientations. The AR-D group used two physical bar magnets, while the CompSim students had simulations that allowed them to explore these arrangements. Finally, the students were asked to explain the differences and similarities between their predictions and their observations.

This type of activity is a popular format for science learning activities and allows for students to externalize their mental model of a construct and then test it against observations (Gunstone, 1990). Students answered questions via Qualtrics, an online survey system, while exploring with their partners. While this system is not commonly used in their physics class, the students have had experience with online assignments for the past few years and were comfortable with answering questions this way.

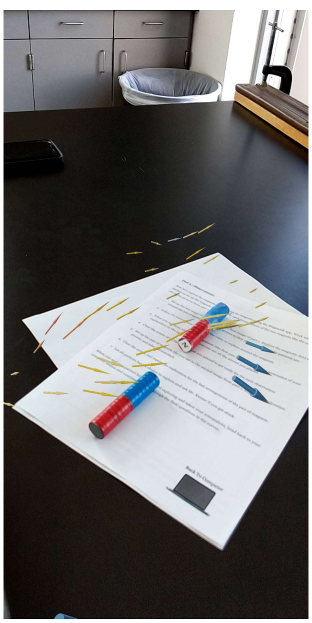
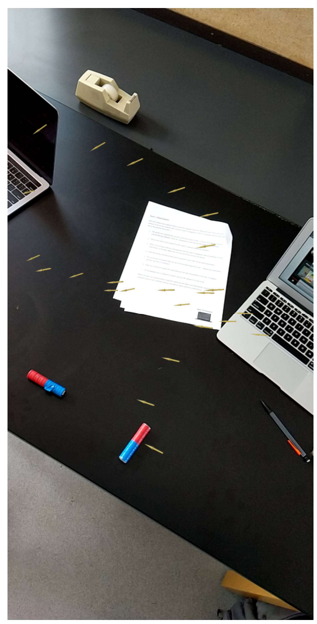
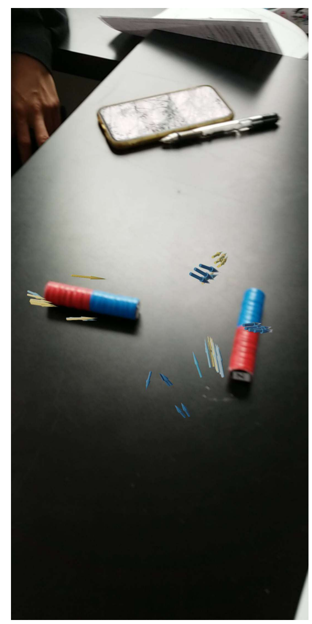
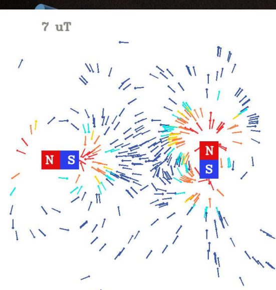
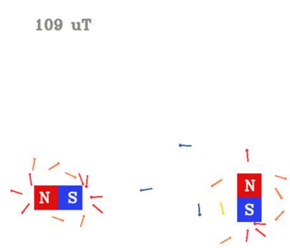
2.3 Measures

2.3.1 Representations Created During Exploration

Students were asked to take screenshots of the representations that they created on each day of the intervention as they explored magnetic fields. The students were asked to use these screenshots to respond to questions during the activity with their partner and were asked to individually choose and upload screenshots that they felt were the most important to show the representations they created. I evaluated these screenshots using the coding scheme outlined in Table 1, to provide some insight into how good of a representation the students were able to create using their technology. . Often this meant that they created a holistic representation, but it did not mean they created an accurate representation. Coding for accuracy would be biased towards the computer simulation technology as there were significantly fewer degrees of freedom for the students to explore. The implications of this limitation will be further discussed in Chapter 4. The coding scheme in Table 1 was used for this question and provided an acceptable value for IRR (κ = .807).

Table 1

Coding scheme for representations created during exploration with technology.

Code	Good Representation	Average Representation	Poor Representation
Description	The images that were uploaded as artifacts on average showcase: - A wide spread of arrows around the magnet - arrows at various distances from the magnet - Show a quickly visible pattern of the magnetic field arrows	The images that were uploaded as artifacts on average are widely placed, but do not show a coherent pattern.	The images that were uploaded on average do not showcase widespread placement of arrows and cannot be interpreted as a holistic pattern.
AR-D Example			
CompSim Example			No Examples

2.3.2 Hand-Drawn ERs

A common strategy to evaluate representational competency is through the assessment and exploration of their own created representations. Students were asked to *individually* draw a representation of a magnetic field around a single bar magnet on the second day of their exploration—before they began their exploration around multiple bar magnets. At the end of the second day, the students had just finished exploring a single bar magnet and this task allowed me to see how they would translate this exploration to a 2D paper representation. The students were encouraged to use arrows to represent the magnetic field.

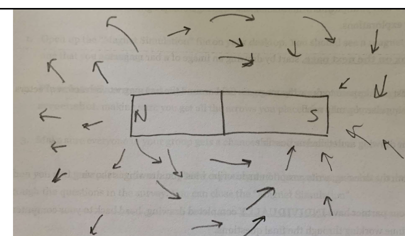
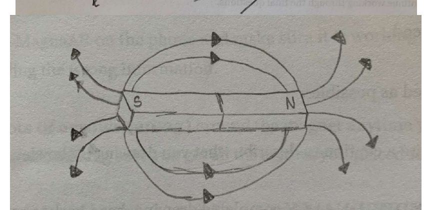
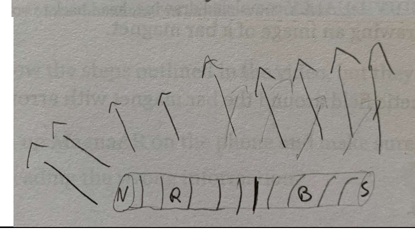
The hand-drawn ERs were converted to quantitative data using categories that had a relevant connection to the ideas of representational competence and exploration. Two coders used a coding scheme to evaluate the hand-drawn images was based on magnetic field accuracy. Each response was coded based on level of accuracy in describing and depicting magnetic fields using prior research for a framework of understanding about magnetic fields (Borges & Gilbert, 1998; Ding et al., 2006; Maloney et al., 2001). To assist in interpreting drawings that may look similar, but represent different ideas, students were asked to provide a description of their drawing which was evaluated in concert with the drawing itself. The exact prompts and questions the students answered are presented in Appendix B. After a few rounds of coding with two independent raters, an acceptable value of IRR was reached ($\kappa = .703$). The level of accuracy was coded on three levels: incorrect, partially correct, and correct. A summary of the final coding scheme is shown in the Table 2 below with examples.

2.3.3 Pretest and Posttest

A measure was developed in conjunction with other researchers to assess the participants' representational competence and content knowledge with magnetic field representations that consisted of questions adapted from well-known physics textbooks and from experienced physics teachers including the primary researcher. This was a necessary step as many of the valid measures that could be used for this content area are not specific enough or appropriate for the high school level (e.g. Li & Singh, 2017; Maloney et al., 2001; Samsudin et al., 2015). This assessment was given as a pretest and administered again as a posttest. The test was comprised of 18 items: 12 computerized and 6 paper-based questions.

Table 2

Coding scheme for hand-drawn ERs

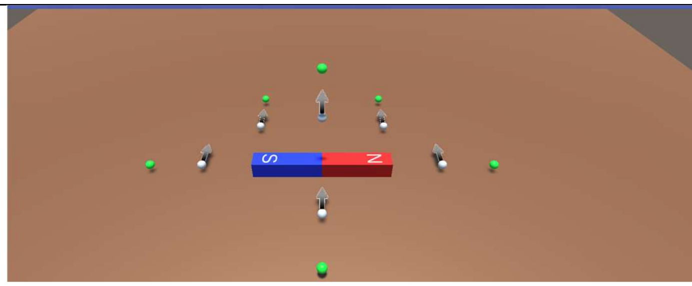
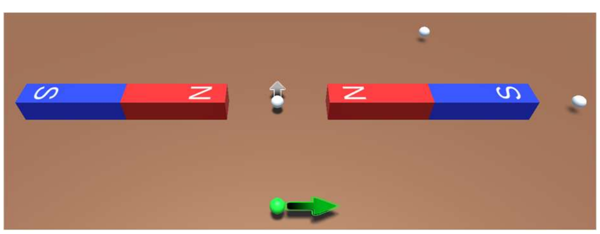
Code	**Name**	**Description**	**Example**
2	Correct	Inclusion of polarity of the magnetic field with a directionality from North to South pole. Formation of a "arced" pattern (*almost full understanding*)	
1	Partially Correct	One of the features from "Correct" code missing, but still shows a general understanding (*incomplete understanding*)	
0	Incorrect	Major aspects of the magnetic field are missing or completely incoherent field drawing and explanation.	

Unfortunately, reliability across the 18 test items was low (α_{post} = .593). This led us to do a careful analysis of relationships among items and an exploration of item content validity. Nine of the test items were found to be inappropriate measures either because they were negatively correlated with several items or because they had poor construct validity. Questions with poor construct validity focused on skills outside of the representational and conceptual knowledge of a magnetic field around a bar magnet. These poorly constructed 9 test items were dropped from the analyses, leaving 9 test items with a moderate level of internal reliability (α_{post} = .701). The 9 questions that were preserved for analysis assessed students' understanding of the magnetic field around a bar magnet. These items centered on the ability to recognize the polarity of a magnetic field and the reduction of a field as distance from the magnetic source increases. Some items asked for the students to interpret the magnetic field around the Earth with the knowledge that it behaves like a bar magnet, while others asked for the magnetic field generated by the interaction of a pair of bar magnets—a physics concept known as superposition.

There were three types of questions on the assessment. Two questions were verbal multiple-choice (MC) questions, six were diagram MC questions, and one was an open-response question. Seven of these nine questions were graded on a binary scale of correct-incorrect, but two multi-part questions were scored on finer-grained 4 and 6-point scales but were out of 1 point. A single question was graded on a 3-point scale ranging from incorrect to partially correct, to correct, but was also out of 1 total point. IRR on this question was good (κ = .871). The maximum achievable score on the pretest/posttest was 9 points. Table 3 provides examples of assessment items and a short description of the scoring method. Appendix A provides the full paper assessment. The computerized assessment is still in development and is not available for full presentation.

Table 3

Example of Pretest/Posttest Assessment Items

Question Type	Example and Answering Method	Scoring Method
Verbal MC	 Students choose an option from the verbal/written out answer choices. In this case they choose if the magnetic field vectors at twice the distance from the gray vectors are “Shorter”, “Same”, or “Longer.”	Scored on a binary scale for right/wrong
Diagram MC	 Students drag the white figure to the location on the Earth that connects with the orientation of the ambient magnetic field shown in the image.	Scored on a binary scale for right/wrong
Diagram MC (multi-part)	 Students had to place a magnetic field arrow at each location by clicking on the dot/sphere and rotating	Each dot was individually scored on binary scale of right/wrong and

	the arrow to one of 8 fixed locations (like the cardinal directions on a compass). The students then had to choose the length of the arrow.	contributed to ¼ of a point.

2.3.4 Intrinsic Motivation Survey

To assess the level of intrinsic motivation for the students in this study, questions were adapted from the interest/enjoyment scale of the intrinsic motivation inventory (IMI). The IMI was developed by Ryan and colleagues (Plant & Ryan, 1985; Ryan, 1982) and has been used in various studies both for science education and novel immersive technologies (Buchner & Zumbach, 2018; Taskiran, 2019). Students were asked to respond on a 7-point Likert scale to eight statements adapted from the IMI's interest/enjoyment scale. Four questions were framed around the students' enjoyment of the activity, such as: "I enjoyed doing this magnetic field activity very much." The other four statements assessed enjoyment of the technology, such as: "I would describe my magnetic field exploration technology as very interesting." The four questions in each category were averaged to create one score for the intrinsic motivation towards the technology and another towards the activity. The full survey is provided in Appendix C.

2.3.5 Demographic Surveys

I also wanted to explore whether the two groups differed in their preference for science and their familiarity with magnets, magnetic fields, and technology. The students in the study answered a single multiple-choice question for each of these categories that filed them into four groups from low to high. All questions are provided in Appendix C in the informational survey.

Chapter 3: Data Analyses and Results

3.1 Baseline Analyses

Baseline analyses were done to determine whether the two conditions differed at the start of the study. There were small counts within some categories in each question, therefore a set of Fisher's exact tests were conducted to compare frequencies. These tests found that there was no significant difference between the groups based on their science preference ($p = .065$), familiarity with magnets ($p = .548$), familiarity with magnetic fields ($p = .853$), familiarity with computer simulations ($p = .620$), or familiarity with augmented reality ($p = 1.000$).

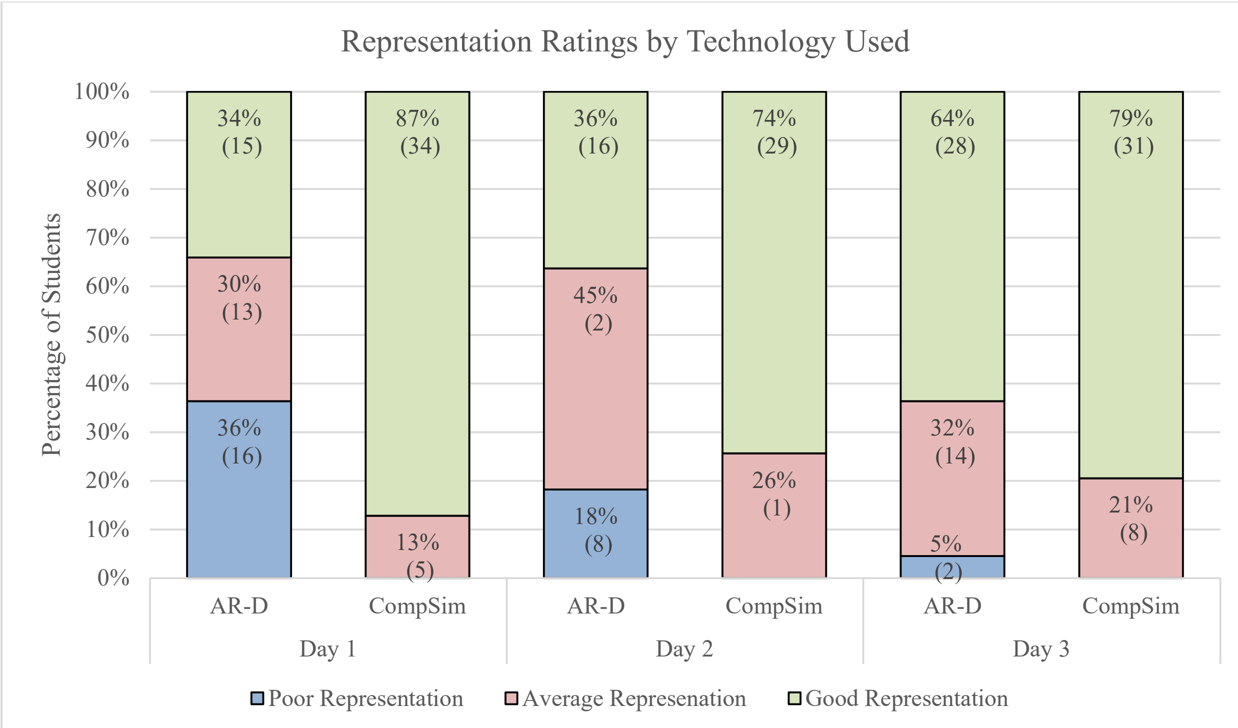
Baseline analyses were also completed on the groups based on the mental rotation test and the scientific reasoning test. Based on two one-way ANOVA analyses, the groups did not differ on the MRT ($F(1, 75) = 0.154$, $p = .696$) or the scientific reasoning test ($F(1, 75) = 0.599$, $p = .441$). Baseline analyses were also completed on the magnetic field pretest. The score on the pretest was from a minimum of 0.25 to a maximum of 6.83 with a mean of 3.01 points out of 9 total points. A one-way ANOVA found that there was no difference in conditions ($F(1, 75) = 0.002$, $p = .978$).

3.2 RQ1: How did AR-D and CompSim students differ on their technology-created representations?

From the initial 97 students that participated in the study, 83 students had valid exploration data. Figure 7 shows the percentages of students that created poor, average, and good representations when exploring with their technology. This indicates that there may be an effect of both time and technology used on the exploration score received by the student.

Figure 7

Representation rating distribution by group across three days of instruction.



The categories that were used to quantify the images provided from the students' exploration with technology were ordinal in structure and were applied in the same manner for images across three time points. This required performing a repeated measures ordinal regression which was done through Generalized Estimating Equations (GEE) in SPSS. The GEE option allows for producing more flexible repeated measures models that can accommodate for noncontinuous outcomes, such as the ordinal outcome of explorer rating. A note should be made about the concern with the 0 counts for bad explorers within the computer simulation group. The presence of this category is important to show a picture of what representations the students created and the affordances associated with the technologies. The following ordinal logistic repeated measures analysis will include this category, but the findings should be accepted with caution due to the deviation from the necessary criteria for this analysis.

The model that was fit for this data was evaluating the effect of time and the type of technology on the explorer rating of the images generated during the instructional exploration.

The model found that the interaction between time and technology was significant ($\chi^2(2) = 7.897$, $p = .019$). Follow-up regression analyses found a significant effect of time for the students that used the AR-D technology ($\chi^2(2) = 17.351$, $p < .001$), but not for the students that used the computer simulation ($\chi^2(2) = 1.658$, $p = .436$). According to the parameter estimates, there is a significantly higher chance of students receiving a higher explorer rating on Day 3 than Day 1 ($\chi^2(1) = 16.089$, $p < .001$), but not a higher explorer rating on Day 2 than Day 1 ($\chi^2(1) = 1.557$, $p = .212$). A set of follow-up chi-square analyses shows a significant difference in explorer rating by group for Day 1 ($\chi^2(2) = 26.719$, $p < .001$) and Day 2 ($\chi^2(2) = 14.842$, $p < .001$), but not for Day 3 ($F(1, 81) = 3.500$, $p = .174$).

3.3 RQ2: How did AR-D and CompSim students compare on drawn representation accuracy?

Of the 97 students that participated in the study, 77 students had full pretest/posttest data and three-day exploration data and could be included in this analysis. Table 4 below shows distribution of students within each scoring category for the hand-drawn images. An ordinal logistic regression of score by group found that participants were more likely to generate more accurate representations if they were using the computer simulation ($\beta = 2.085$, $\chi^2(1) = 20.424$, $p < .001$).

Table 4

Distribution of Student Scores on Day 2 Hand-Drawn Magnetic Field

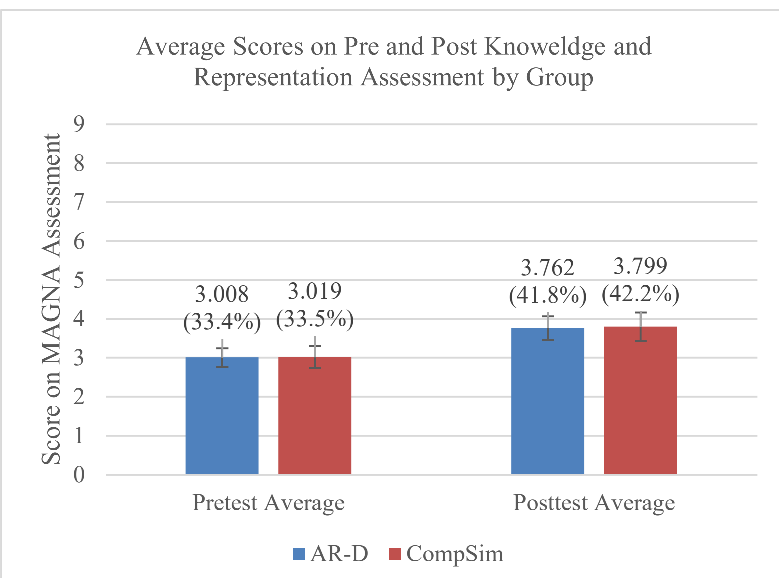
	Incorrect Representation	Partially Correct Representation	Correct Representation
AR-D Technology	28 (68.3%)	9 (22.0%)	4 (9.8%)
Computer Simulation	10 (27.8%)	4 (11.1%)	22 (61.1%)

3.4 RQ3: How did AR-D and CompSim students compare on learning outcomes?

Of the 97 students that participated in the study, 77 students had full pretest/posttest data and three-day exploration data and could be included in this analysis. Figure 8 below shows descriptive data of pretest and posttest scores. A univariate ANOVA was conducted evaluating the effects of posttest indicating no significant differences on posttest by condition ($F(1, 75) = 0.006$, $p = .939$). The full results are shown in Appendix D. These results indicate that the AR-D technology does not have a benefit or detriment to students' learning of magnetic field concepts and representations. However, a paired t-test showed that combining across conditions, students' scores increase by 9% from pre to posttest, which is a significant gain ($t(76) = 4.062$, $p < .001$). More results are shown in Appendix D.

Figure 8

Average pre-test and post-test measurements split by group.



Note. N = 77. The number in the parentheses is the percentage score on the test. Maximum score is 9 points.

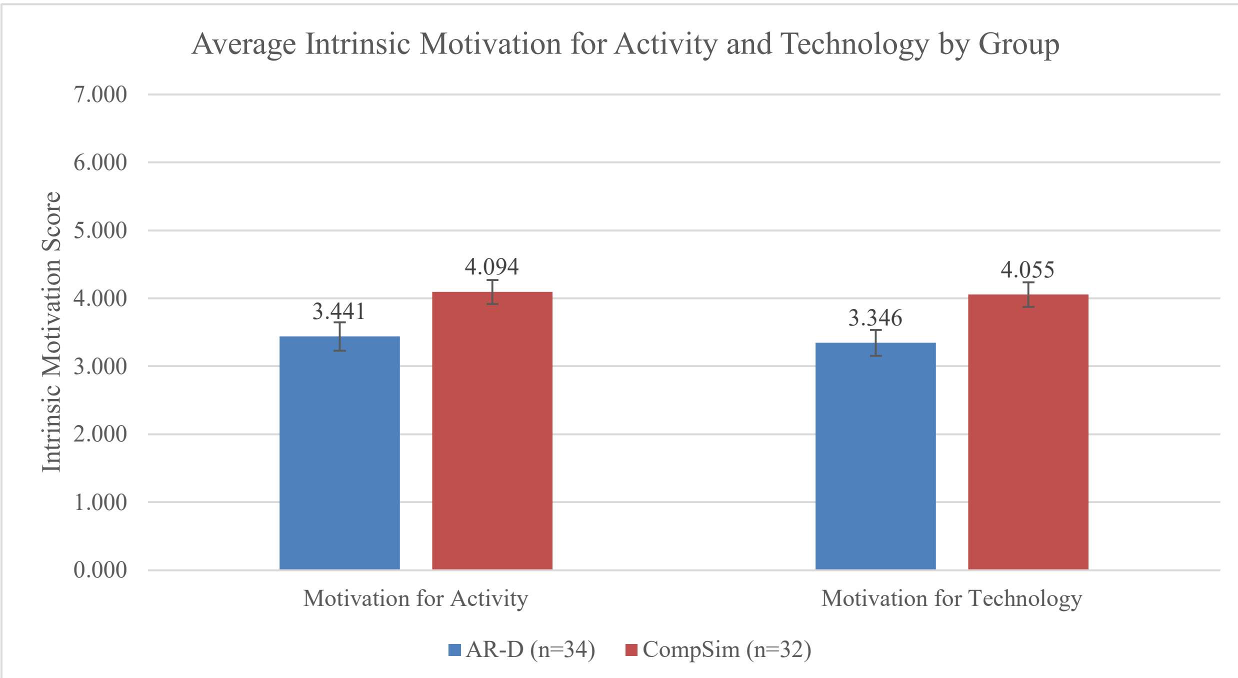
3.5 RQ4: How did AR-D and CompSim students differ in their level of intrinsic motivation?

Unfortunately, several students did not have time to complete the intrinsic motivation survey, which was given at the very end of the intervention, leaving a sample of 66 students for the following analysis. Figure 9 provides a graph to show the differences by group on each motivation measure. I explored condition differences on two measures of intrinsic motivation: enjoyment of the technology and enjoyment of the physics activity. These two measures were strongly correlated ($\rho = .877$, $p < .001$), so a MANOVA analysis was conducted to test condition differences.

The MANOVA analysis resulted in a significant result (Wilks $\Lambda = .898$, $F(2, 63) = 3.578$, $p = .034$). Follow-up ANOVA analyses found conditions differed in both intrinsic motivation to engage with the activity ($F(1, 64) = 5.680$, $p = .020$) and intrinsic motivation to engage with the technology ($F(1, 64) = 7.258$, $p = .009$). These analyses show that students who explored with the computer simulation technology reported higher levels of intrinsic motivation. More information on descriptives are shown in Appendix D.

Figure 9

Comparison of the levels of intrinsic motivation by group.



Note. This is the average of 4 questions in each category. The maximum average score was 7.

Chapter 4: Discussion and Conclusion

The work in this dissertation aims to understand how the use of a novel technology, augmented reality, could be useful in instructing students about magnetic fields and their representations. The investigation within this work looked towards the value of AR through three lenses: characteristics of exploration and representations generated during instruction, performance on a magnetic field conceptual knowledge and representational competence assessment, and motivation to engage in magnetic field instructional activities. Although there is ample research demonstrating the value of using AR technology for learning, the data in this work provide evidence of the complexities of implementing AR in a classroom setting. Contrary to many of my predictions, students using AR-D explored less productively, created less accurate and domain-accepted representations, and were less intrinsically motivated than student using the computer simulations. However, there were ultimately no differences in learning across the groups of students.

4.1 Interacting with Representations

As learners engage with a conceptual domain, the skills of exploring, interpreting, and creating ERs are critical for developing domain understanding. In this work, the first step—exploration—allowed for the students to have an opportunity to visualize the invisible magnetic field. Unfortunately, students who engaged with the AR-D software in this work had a harder time exploring on the first two instructional days but improved to match the CompSim students after the students were provided an in-person model of how to use the AR-D technology on the third day of exploration. While the improvement in representations created by students can be partially explained by increased familiarity with the technology over time, the students may have benefited from pointed instruction on *how* to use the AR-D for the varied tasks assigned each day. My informal observations found that many students understood how to interact with the computer simulation and could easily work with their partners, while students were less familiar with AR-D and struggled with balancing learning the skills to use the hardware, the software, and the content simultaneously. I attribute this difference in proficiency due to a combination of the unfamiliarity with AR-D technologies, the lack of clear training to use the software, and the familiarity with 2D computerized virtual science simulations. Even after two full days of exploration with AR-D to familiarize the students with AR-D, students were observed to be uncomfortable and could benefit from more specific and modeled instruction (given day 3).

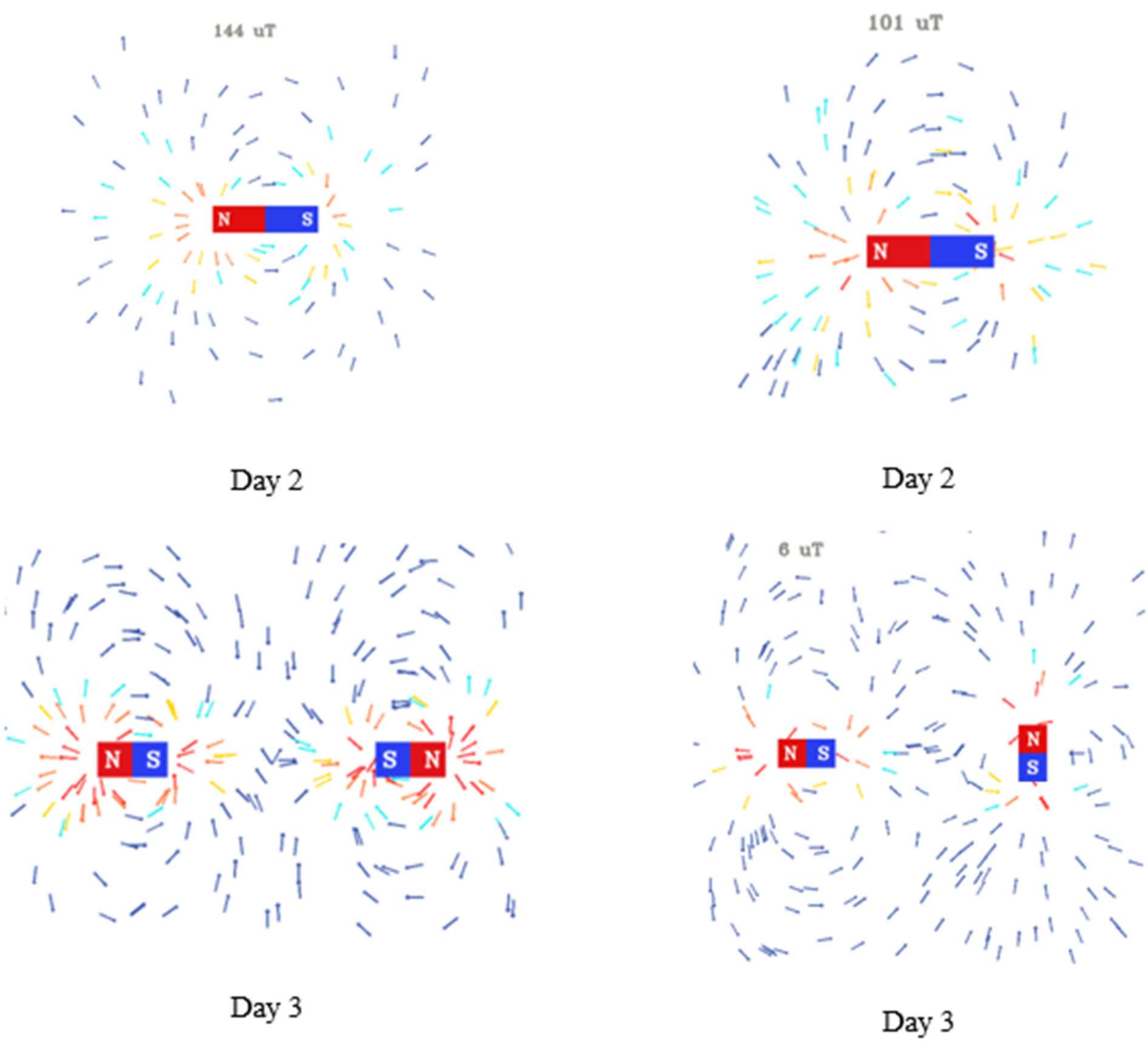
After the students explored, I reviewed the screenshots that students provided of their observations with the technology to provide a better picture of the types of representations the students created during exploration. I found two things. First, the representations created by the students using AR-D technology were highly variable and seemed to be hard to interpret, while the CompSim representations were consistent and decodable. Figures 10 and 11 showcase examples of "good explorations" by CompSim students and AR-D students respectively. The CompSim images show more consistency and pattern interpretability: there is a gradual directional change as you move around the magnet, there are changes in color as you move away from the magnet, etc. Essentially the students are getting a single, simple, consistent pattern of what the magnetic field looks like around different arrangements of bar magnets.

By contrast, the AR-D examples show a dramatic difference between the quality of images. Some images show the magnetic field surrounding the magnet, while others restrict that "surrounding exploration" to only one side of the magnet. We can imagine that each of the images constitutes a single angle of view, and the students are then meant to integrate the various 2D images into a whole 3D mental model of the magnetic field. The task of integrating these single views to a 3D model is known to pose a challenge to learners and even if students are capable could result in highly variable understandings and mental representations of a magnetic field. For example, the bottom-left image of Figure 11 could generate the belief that the magnetic field only exists above the magnet in a linear pattern, while the bottom-right image may indicate the field is only trying to point towards the red end of the magnet on the right. This inconsistency and pattern ambiguity could muddle what the students focused on and result in varying, and erroneous, understandings of magnetic field representations.

So far, I have provided some clarity into the challenges associated with the digital ER creation. However, I also found that CompSim students created more accurate hand-drawn representations than the AR-D students. I believe this arises from three factors. First, the students using the computer simulations had the advantage of a larger screen and a familiar hardware setup. This could have facilitated a lower barrier for entry in more productive exploration and creation of representations. However, the computer simulation also provided a more consistent, easier-to-decode visualization, as described above. The students are more familiar with 2D images, especially in relation to magnetic fields, as many representations that are commonly used are shown in a 2D format. This may have created a more accessible understanding of the structure of the magnetic field. Finally, the computer simulation provided access to a 2D representation that can easily be translated to a 2D paper drawing, while the AR-D showed 3D information that may have been harder to translate. While the AR-D condition had the potential to showcase more complete representations of the magnetic field around a magnetic source, the interpretations of their observations may have been too challenging. Research shows that students struggle to transition from 3D to 2D (e.g. Keenan & Powell, 2020), and even with scaffolding on how to *use* AR-D, the students may have needed more time to familiarize themselves with how to translate

Figure 10

Examples of "good explorer" student ERs from CompSim.



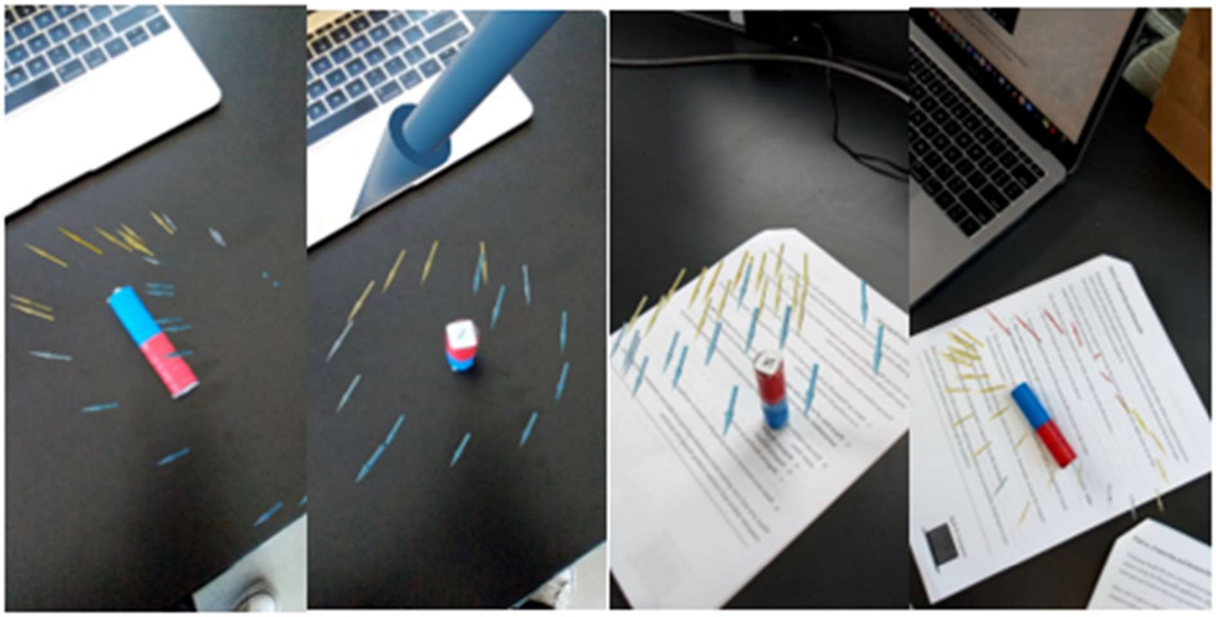
from 3D to 2D. Magnetic fields are already a very challenging topic—even instructors wrestle with the complex ideas. The extra layer of an obtuse tool, both in usability and interpretation, may have hindered their ability to access the deeper ideas needed to develop an understanding of the concepts.

4.2 Why were there no learning differences?

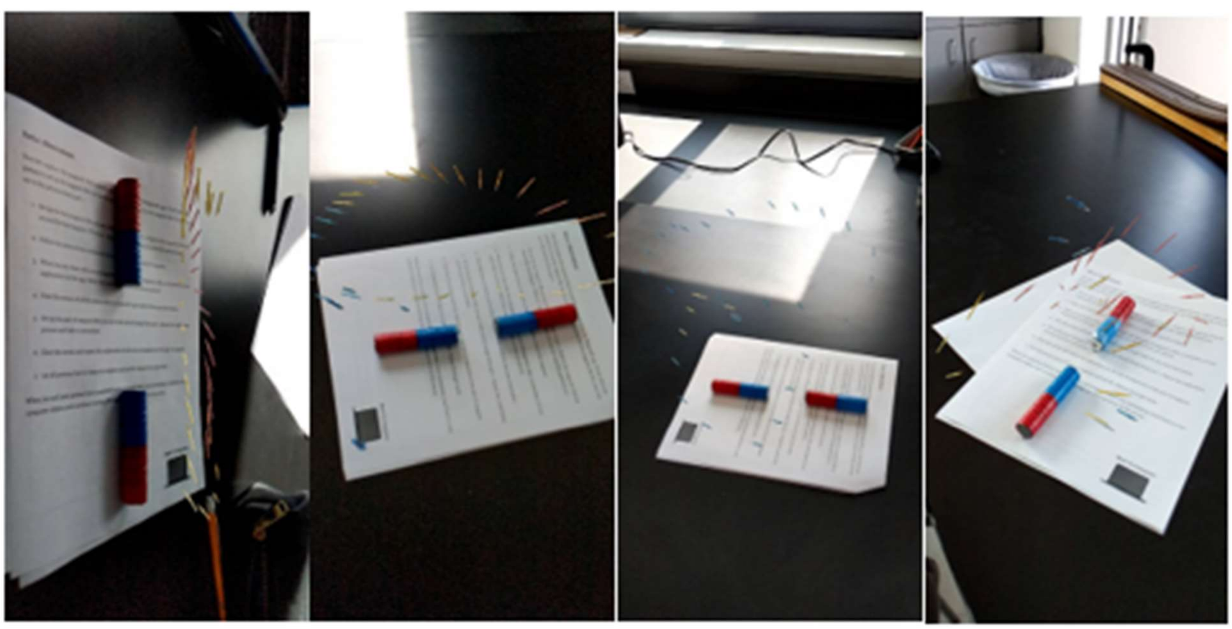
Despite these differences, students had similar learning gains across both groups from

Figure 11

Examples of "good explorer" student ERs from AR-D.



Day 2



Day 3

pretest to posttest. Although this outcome does have some backing from prior investigations comparing augmented to virtual reality (Liou et al., 2017; Radu & Schneider, 2019), comparing VR to simulations and physical models (C. E. Brown et al., 2021), and comparing AR to computer simulations (Chang et al., 2014), this result was unexpected in this implementation as it counters the expectations from prior work (Garzón & Acevedo, 2019). A possible explanation for this could lie in how the material was presented to the students. Magnetic fields are a challenging concept for learners and instructors and encourage the use of clear representations for successful instruction. While the CompSim and AR-D students had similar tools for exploration within the software, the additional dimension afforded by AR-D could have counteracted any benefit to using the immersive technology by both creating more flexibility in creating and observing the magnetic fields as described in the previous section. These challenges could have been overcome by developed scaffolding or higher instructional dosage. In RC literature, instruction is often designed for weeks, or even full semesters, asking students to repeatedly refine their ERs as they get deeper into a course by providing feedback or catered observational experiences (e.g. Bergey et al., 2015; Hill et al., 2015). Through this extended implementation, students gradually develop more sophisticated and domain-accepted conceptual understanding and representational competence. The instruction students received in this study was short and open-ended. This may not have provided students with opportunities to get comfortable with the technology or training on how to decode their observations of the representations.

These learning results could also be explained by assessment design. As mentioned earlier, only half of the assessment was preserved in this work due to construct validity and low correlations between questions. Magnetic fields are a complex topic and any misworded questions may have been even more difficult due to the challenging content. In addition, the items may not have been sensitive enough to capture learning differences. Researchers and instructors are still investigating the benefits of immersive technologies and assessment design strategies we currently have may not be appropriate (Lindgren & Johnson-Glenberg, 2013). This combination of unrefined and potentially invalid questions may have masked learning gains.

4.3 Are computer simulations really more motivating?

While much research shows that students are generally more motivated when using augmented reality technology, the data collected in this study provide evidence to the contrary. Why then, did the AR-D condition report lower intrinsic motivation? Analyses of the exploration conducted by the students show that the images they saw may have been too difficult to understand and decode—if both the technology and the content were challenging and the students received little feedback to help direct them towards "understanding," why would they be motivated? This may have created a loop of failing to see positive outcomes without a good way out (Bransford & Schwartz, 1999; Kapur & Bielaczyc, 2012).

A choice was made during the study design process to have the students work with partners, both to create a more authentic classroom experience and to combat the potential "loop of failing" associated with challenging, open-ended activities. The use of the mobile AR technology should have afforded students with a *tool* to work together to interpret the world rather than a stationary and disconnected activity. Contrary to what was expected, students using AR-D were observed to have more difficulty in interacting productively with their partners, making the activity less collaborative (e.g. Lin et al., 2013). Students openly made comments that the computer simulation was a "fun activity," but no such comments were overheard from AR-D students. While this evidence is anecdotal, it does suggest that students using AR-D may have felt alone and confused leading to lower levels of motivation.

While this may seem to imply that immersive technology like the AR-D used here, with all its novelty and "cool" effects, may not provide a motivational benefit above and beyond other technologies, I would argue that the story is more complicated in this case. All the students were tasked with learning a complex concept and the students using AR-D were asked to do this with a novel and somewhat imprecise tool for the goals of the instruction. The AR-D tool was provided on a small screen and no prior or consistent instruction was given to lead the students to productive behaviors in using the technology throughout the instruction. These challenges may have been a larger contributor to the AR-D students' lack of intrinsic motivation rather than the technology itself.

4.4 Implications and Future Directions

This dissertation work provides evidence that contributes to the intersection between the use of immersive technology, the development of representational competence, and physics education. This work shows that the implementation of AR as a tool for creating and reasoning with representations is not a straight-forward process. Compared to more familiar technologies, AR provides more flexibility in exploring representations, however these representations exhibit more variability and could hinder interpretation. In addition, educators cannot rely solely on the appeal of introducing a new technology as a source of motivation but should consider how these technologies can interact with the way that students observe, reflect, and collaborate. There are three main recommendations that I would make for implementing the more free-exploration style AR programs for developing representational competence.

First, teachers should direct instruction towards helping students create more effective ERs using the technology that can help more completely access the underlying concepts. The creation of representations requires feedback and guidance to help in understanding what is being seen. This work shows that even with the constraints provided by centering ER creation around physical objects and interactions, the students were still challenged by creating and interpreting good images of magnetic fields. Teachers could have helped reorient students both physically and mentally as they explored with free-form AR-D applications, increasing the likelihood of clearer digital representations. Second, teachers should make sure to provide more focused instruction on how learners can integrate 2D views into a 3D model of a phenomena. The data showed that students using AR-D had the flexibility to look at a 3D representation of magnetic fields through varied angles, but they may have had challenges integrating their views into a 3D structure. This could have limited the students in developing a clear representation of a field. Finally, teachers should help students to translate a 3D model or structure to 2D. This 2D to 3D translation skill is still acknowledged to be a challenge for learners. This work showcased that students were able to take a 2D computerized representation and translate it to a 2D paper representation, but this was more difficult for the students using AR-D. In addition, the assessment provided representations that were slightly different in how they presented dimensionality, which could have created another hurdle. Many modes of communication in science require the use of 2D modalities, be on paper or in a presentation, and require that students take 3D information, via simulations or physical phenomena, and translate it to various formats. Helping students to navigate this transition is something that is crucial in developing a stronger understanding of complex phenomena, like magnetic fields.

In addition to recommendations for teachers, the results also raise interesting questions for future research. First, the technology was limited in its presentation, only able to be implemented through a mobile cellular device and often experienced visual ‘hiccups’ due to the nature of this implementation. Primarily, these phones provide very little visual real-estate which could affect the ways that students learn (Kim & Kim, 2012; Wang, 2017); however, when this constraint combined with the frustration of software issues, students could have had a difficult time accessing the content. Future research should establish what connection AR-D hardware could have on development of RC with magnetic fields. Second, a measure had to be developed for this work as there was not an adequately developed inventory for magnetic fields at an introductory level (Li & Singh, 2017; Maloney et al., 2001) or an assessment on magnetic field representations. However, the measure implemented may not have been enough to tap into learning differences. Research focused on RC often evaluates students using more qualitative methods such as interviews and video recordings, which were not implemented in this research. Future research should focus on continuing to develop better inventories in both areas geared towards a younger population while also accounting for the affordances and skills addressed by AR technology. These inventories should be informed by qualitative methods that can characterize the conceptual changes created by using AR. Third, learning in classrooms are not individual and an attempt was taken in this work to provide a collaborative experience for the students, however its success was ambiguous. There is research that has focused on understanding how collaboration could be facilitated with AR (Birchfield & Megowan-Romanowicz, 2009; Lin et al., 2013; Martín-Gutiérrez et al., 2015; Unahalekhaka et al., 2019), but more work should be done on how to connect this collaboration with the development of representational knowledge of complex topics like magnetic fields.

4.5 Conclusion

This dissertation provides some evidence for potential problems that could arise from the integration of novel immersive technology in a classroom setting, specifically for addressing the creation and reasoning with representations. The classroom is a complex environment with numerous interactive features—what looks promising at the surface could be more complicated as students begin to interact with it. New technologies come with new levers that can be adjusted and more factors to consider for successful implementation. In this work, the AR-D technology was designed to show students a more authentic representation of the magnetic field, however this intention was limited by a confluence of factors. Primarily, students showed difficulty in creating and interpreting representations they saw when using the AR-D technology, supporting the idea that students need more guidance in how to create and interpret representations.

However, designers and instructors need to consider factors beyond just instructional scaffolding, also accounting for how students' interactions can be influenced by screen size and visual field limitations and how these hardware-associated factors interact with the subject matter. Many concepts in STEM involve the integration of 3D and 2D factors, asking students to process information in multiple modes and integrate these visualizations—without proper consideration with how best to show and connect these visualizations, AR technology may just be "another thing" rather than a useful tool for developing representational competence.

While the data from this dissertation raise more questions than provide answers, this work is continuing to open the door to the connection between AR and ERs. As a technology that provides views that others cannot, teachers can use AR to provide more depth to content that is taught. I imagine that teachers can use AR to show dynamic force diagrams and changes in energy—creating richer experiences that are more deeply connected to relevant representations. However, this work shows that on its own, AR cannot teach students to create and reason with ERs. AR is still just a tool and learners need to also be taught on how to use it.

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Appendix A: Paper Knowledge Assessment

Instructions: Finish answering these questions on this paper. Make sure to clearly circle the answers. When you are finished, follow the links at the end and complete the online surveys!
Magna Test – Paper Questions

1. The image to the side shows a magnetic field <u>around a bar magnet</u>.

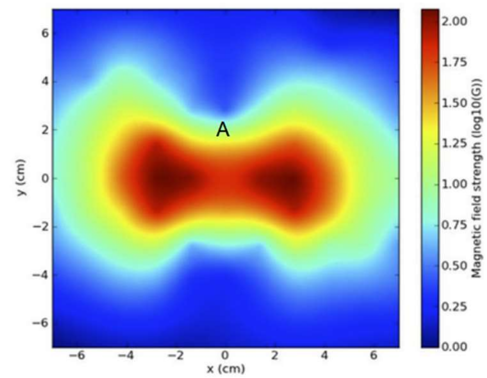
   How will a magnetic field vector look when it is placed at point A?

   a. The arrow will point up or down.

   b. The arrow will point to the left or right.

   c. The arrow will not point in any direction.

   d. There is not enough information to know.



2. In the previous image, which end of the bar magnet is the "North Pole"?

   a. The right side of the magnet.

   b. The left side of the magnet.

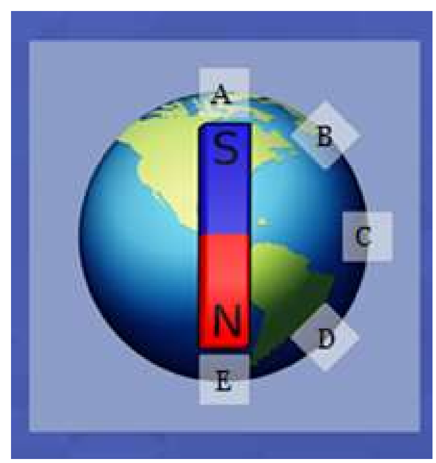
   c. There are no poles to this magnet.

   d. There is not enough information.

3. As shown below, the Earth's magnetic field is like a bar magnet – but it's actually flipped upside down!

   If a person was observing the magnetic field in an area and saw the vectors pointing down and to the left, where would they be on the Earth?

   Circle A, B, C, D, or E as your answer on the image!



4. In between two identical magnets, as shown in the image to the right, what would the magnetic field be at point A?

   a. None

   b. Weak.

   c. Very Strong

d. There is not enough information

5. What happens to the strength of a magnetic field created by a magnet as you move farther away from the magnet?

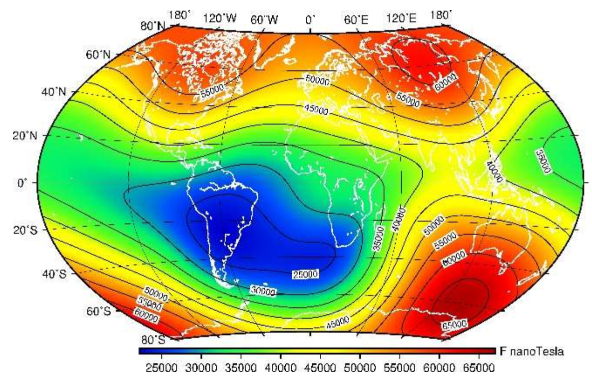
   a. The strength of the magnetic field increases forever

   b. The strength of the magnetic field stays about the same

   c. The strength of the magnetic field decreases and disappears

   d. The strength of the magnetic field decreases forever

6. The image below shows information about Earth's magnetic field. Which of questions can you NOT answer using this diagram?



   a. Where the Earth's magnetic field is the weakest?

   b. Where is there "no magnetic field" on the Earth?

   c. Where is the "north pole" of the Earth?

   d. Where are the "magnetic poles of the Earth?

Appendix B: Learning Activity

Table B1 shows the differences in what technology the students were using as they were exploring magnetic fields in this instruction.

Table B1

Technology and Activity Differences in Groups

	AR-D Group	**CompSim Group**
ER and Physical Connection	Magnetic field is presented overlayed on the real-world (the dynamic spatial overlay)	Magnetic field is presented on a computer screen separate from the real-world
Visual Representation of Magnetic Field	Create ***3D*** virtual vector depicting the magnetic field at that location	Create ***2D*** vector based on mouse position depicting the magnetic field at that location
Action of Participants	High ***physical*** movement of mobile device to "see" the magnetic field	Low movement, but familiar interaction with mouse and keyboard
Nature of the Vectors	Vectors are multicolored, show small changes in size due to magnitude, and can be seen/viewed from multiple angles in 3D	Vectors are multicolored, are all a single size, and can be seen/viewed from a single angle like a paper representation in 2D

The following worksheets were provided for the students in the AR-D group to use with their partners as they were exploring. All links are active and will direct to a Qualtrics survey that the students had to fill out individually as they were working through the instructional activity. The

CompSim had very similar worksheets, but were provided with links that led them to Qualtrics surveys that referenced their simulations, rather than the AR-D technology.

Welcome to Magna Day 1!

First make sure that you have one packet in front of you for every partner and a computer for each one of you. You will individually be completing a survey on the computer.

Next, go to the following webpage <u>ON YOUR OWN DEVICES</u> and get started! Have fun!

Bit.ly/Day1MSA

Day 1 – Exploration around the Classroom

Instructions: The goal for today is for you and your partner to get used to using the phone application: MagnaAR. This technology will allow you to visualize the magnetic field in the world around you.

Let's start by exploring three areas around the room: YOU DON'T HAVE TO GO IN ORDER!

1. Close to the door(s) out of the room
2. As far away from the door(s) as possible
3. Somewhere halfway in between (middle of room)

Explore the magnetic field in each of the areas like you saw in the video. Take note of where the front of the room is–**this is facing EAST**! This knowledge allows us to be consistent with how we are looking!

Take a screenshot of what you created while exploring. Once you are done, move on to the next area.

When you and your partner have completed exploring all three areas and taken your three screenshots, return to the computer station and continue working through the survey. *Ask Mr. Kumar if you have any questions.*

Back To Computer

Drive Link!

Follow the instructions on the survey to upload your screenshots to the google drive folder with your name and repeat for your partners' folder. You will have to copy over the pictures to at least one person in your group.

<u>**Follow the directions on the video in the survey!**</u>

If this doesn't work, ask Mr. Kumar and go to this page on your phone:

bit.ly/Day1DriveA

Welcome to Magna Day 2!

NAME: _______________________PARTNER___________________________

Make sure that you have one packet in front of you for every partner and a computer for each one of you. You will individually be completing a survey on the computer.

Next, make sure that you have a charged phone, a "bar magnet", and a paperclip.

Next, go to the following webpage and get started! Have fun!

Bit.ly/Day2MSA

Day 2 – Exploration of a Magnetic Field

Overall Instructions: You and your partner's goal for today is to explore the magnetic field around a paperclip and a magnet.

Part 1 – Paperclip and Magnet:

First, let's observe what happens with a paperclip and magnet. Use the materials to explore however you like to get familiar with the interaction.

To get started, you can try the following things:

1. Slowly bring the paperclip closer and farther away from the magnet.

2. Bring the paperclip closer to the magnet on different sides of the magnet.

3. Try to move the paperclip around the magnet in a circle, but leave it always the same distance away.

Once you have done this exploration, go back to the survey and answer the questions.

Back To Computer

Part 2 – Paperclip and MagnaAR:

Welcome back! By now, you and your partner should have seen the video of how to explore around an object using the MagnaAR application. *If you have not done this already, please go back and make sure you go back to the survey and complete it.*

Now, let's explore what the magnetic field looks like around a paperclip only. Make sure to set the magnet aside and pick up the phone now.

You can follow the steps outlined in the video, but they are also shown here:

1. Open up the MagnaAR application on the phone.

2. Explore the magnetic field around the paperclip like you saw in the video.

3. **Place lots of arrows (20-25)** around the paperclip while it is just sitting on the table. **Take a screenshot**, making sure you get all the arrows you placed.

4. Clear the screen of arrows and repeat this when the paperclip is held in your partner's hand. Take another screenshot.

5. Repeat this process again by placing the paperclip anywhere. Remember to keep the magnet away from your exploration for now.

6. Make sure everyone in your group gets a chance to use the simulation.

When you and your partner have completed exploring and taken your screenshots, head back to your computer station and continue working through the questions.

Back To Computer

Part 3 – Magnet and MagnaAR:

Welcome back! Now, let's observe what the magnetic field looks like around a magnet only. Set the paperclip aside and make sure you have just the phone and magnet to work with.

Now, let's use MagnaAR to explore the magnetic field around a magnet. Make sure to set the paperclip aside and pick up the phone now.

You can follow the steps outlined in the video, but they are also shown here:

1. Open up MagnaAR on the phone and make sure it is working properly. Restart the program if it is reading the wrong information.

2. **Place lots of arrows (20-25)** around the magnet anytime you are exploring. **Take a screenshot**, making sure you get all the arrows you placed for all exploration you do.

3. You can explore the magnet in similar ways to the paperclip from the previous part. Here are some ideas:
    a. Magnets on table
    b. Magnets in hand
    c. Magnets standing up versus flat

4. Make sure everyone in your group gets a chance to use MagnaAR.

When you and your partner have completed exploring and taken your screenshots, head back to your computer station and continue working through the questions.

Back To Computer

Part 4:

Last part. You have done a lot of exploring the magnetic field around two different types of objects.

Individually, you and your partner will each make a drawing of the magnetic field around a bar magnet like the one you explored around with MagnaAR.

1. **In the box on the next page**, start by drawing an image of a bar magnet.

2. Use the rest of the space to draw the magnetic field around the bar magnet with arrows/vectors and anything else you may need.

3. Make your drawing as detailed as possible.

4. Underneath the drawing, write a caption to describe what you drawing is showing.

When you and your partner have **INDIVIDUALLY** completed drawing, head back to your computer station and continue working through the final questions.

YOU WILL BE DOING THIS INDIVIDUALLY. YOUR PARTNER AND YOU EACH NEED TO HAVE YOU OWN UNIQUE DRAWING!

Drawing of a Magnetic Field Around a Bar Magnet
Caption of Drawing of a Magnetic Field (Above Drawing)

Drive Link!

Follow the instructions on the survey to upload your screenshots to the google drive folder with your name and repeat for your partners' folder. You will have to copy over the pictures to at least one person in your group. You will have to copy over the pictures to at least one person in your group. Try to avoid looking into other students' folders!

<u>**Follow the directions for what you did on the first day!**</u>

<u>***Hand this packet to Mr. Kumar when you are finished!!!!***</u>

Welcome to Magna Day 3!

NAME: ________________________PARTNER____________________________

Make sure that you have one packet in front of you for every partner and a computer for each one of you. You will individually be completing a survey on the computer.

Next, make sure that you have a charged phone and a pair of bar magnets.

Next, go to the following webpage and get started! Have fun!

Bit.ly/Day3MSA

Day 3 – Exploration of Magnetic Field around 2 Magnets

Overall Instructions: You and your partner's goal for today is to explore the magnetic field around a pair of bar magnets arranged in different ways using MagnaAR to what you have used before.

Part 1 – Predictions:

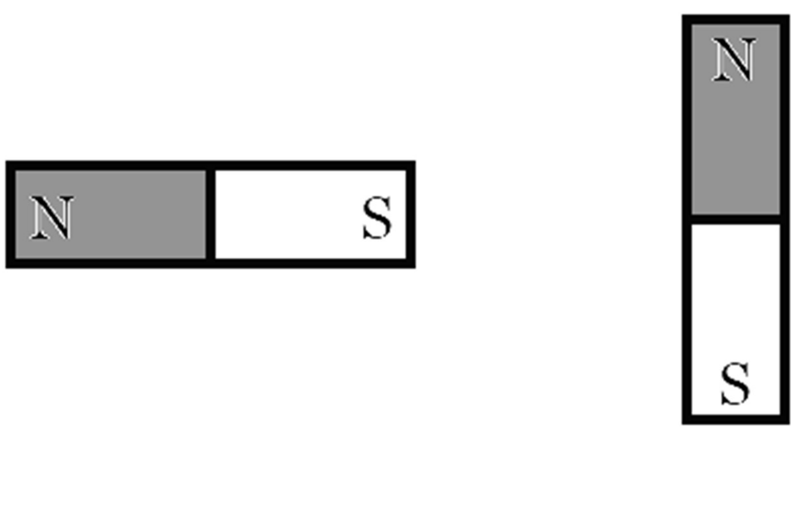
In each of the boxes below, there are two magnets arranged in different ways. Using what you learned from Day 2 and the superposition video, draw your prediction of what the magnetic field will look like in these different situations.

FIRST, WORK ON THIS INDIVIDUALLY. YOU WILL GET A CHANCE TO COMPARE LATER.

Magnetic Field: Arrangement 1

Magnetic Field: Arrangement 2

Magnetic Field: Arrangement 3



When you and your partner have **INDIVIDUALLY** completed your predictions, head back to your computer station and continue working through the questions.

Part 2 – Observations:

Now let's explore the magnetic field around the magnets using the MagnaAR app. Work with your partner to set up the magnets like you see in each arrangement of the two magnets like the ones you see in the pictures from part 1.

1. Set up the two magnets like you see in the first image of part 1. Explore the magnetic field all around the two magnets. Place 20 – 25 arrows so that you can see what the patterns are.

2. Follow the instructions outlined in the video to explore around the magnets.

3. When you are done with one arrangement (the first pair of magnets), take a screenshot of your exploration on the app. Make sure you can see all the arrows you placed.

4. Clear the screen of all the arrows that you placed to get ready for the next observation.

5. Set up the pair of magnets like you see in the second image from part 1. Repeat the exploration process and take a screenshot.

6. Clear the screen and repeat the exploration for the last arrangement of the pair of magnets.

7. Let all partners have a chance to explore and ask Mr. Kumar if you get stuck.

When you and your partner have completed exploring and taken your screenshots, head back to your computer station and continue working through the final questions in the survey.

Back To Computer

Drive Link!

Follow the instructions on the survey to upload your screenshots to the google drive folder with your name and repeat for your partners' folder. You will have to copy over the pictures to at least one person in your group. You will have to copy over the pictures to at least one person in your group. Try to avoid looking into other students' folders!

<u>Follow the directions for what you did on the first day!</u>

If this doesn't work, ask Mr. Kumar and go to this page on your phone:

bit.ly/Day3DriveA

Appendix C: Additional Surveys

Motivational Survey

The following survey was administered to all the students at the end of the survey. The survey was administered online via the Qualtrics system.

Please slide the bar to the best option for each statement.

	Not At All True			Somewhat True			Very True
	0	1	2	3	4	5	6
I enjoyed doing this magnetic field activity very much.							
This magnetic field activity did not hold my attention at all.							
I enjoyed working with my magnetic field exploration technology very much.							
I would describe my magnetic field exploration technology as very interesting.							
The magnetic field exploration technology that I used did not hold my attention at all.							
I thought this magnetic field activity was quite enjoyable.							
I would describe this magnetic field activity as very interesting.							
I thought my magnetic field exploration technology was quite enjoyable.							
I have no idea of what my technology was trying to show me.							

Which of these statements is most accurate for you?

◯ I really would not like to know more about magnets and magnetic fields.

◯ I don't mind learning more about magnets and magnetic fields.

◯ I do want to learn more about magnets and magnetic fields, but only if I learn it in class.

◯ I do want to learn more about magnets and magnetic fields, but only if I can do it on my own.

Which of these statements is most accurate for you? (You can pick more than one.)

☐ I think that the technology that I was using was not useful for learning about magnetic fields.

☐ I think that I needed more time with the technology to learn about magnetic fields.

☐ I think that I needed more instruction on how to use the technology to learn about magnetic fields.

☐ I think that I needed more instruction on magnetic fields specifically to learn about magnetic fields.

List out any questions you have about magnetic fields, the technology you used, or anything else from these 3 days of exploration.

Day 0 - Informational Survey

Introduction Fill out the following!

- ○ First and Last Name ____
- ○ Physics Teacher ____

SciencePreference Which response best describes your experience with science classes?

- ○ I only experience science classes at school and I do not enjoy it.
- ○ I only experience science classes at school and I do enjoy it.
- ○ I like science classes at school and also attend flex and school clubs.
- ○ I like science classes at school and also try to do science activities outside of school.

MagnetFamiliarity Which response best describes your familiarity with magnets?

- ○ I have never used a magnet before.
- ○ I have only used magnets outside of school (refrigerator magnets).
- ○ I have learned a little about magnets in school, but do not know much about them.
- ○ I understand a lot about magnets and could teach someone else.

MagFieldFamiliiarity Which response best describes your familiarity with magnetic fields?

○ I am not familiar with magnetic fields at all.

○ I have heard of the term before, but don't really know what they are.

○ I have learned a little bit about magnetic fields, but would not be able to explain what they are.

○ I completely know what magnetic fields are and could teach someone else.

CompSimFamiliarity Which response best describes your familiarity with computer simulations?

○ This is my first time hearing about computer simulations.

○ I have heard about computer simulations before, but have not used them.

○ I have used computer simulations a few times and understand what they are.

○ I am very familiar with computer simulations and have used them a lot.

ARFamiliarity Which response best describes your familiarity with augmented reality (AR)?

○ This is my first time hearing about AR.

○ I have heard about AR before, but have not used it.

○ I have used AR a few times and understand what it is.

○ I am very familiar with AR and have used it a lot.

Appendix D: Additional Analyses

Table 5 shows the ANOVA analysis full results of the test to determine the technology effects on the posttest knowledge and representation assessment. There were no other control variables included as baseline analyses found no differences between group.

Table D1

ANOVA Results for Posttest by Intervention Group

Predictor	SS	*df*	MS	F	*p*	η_p^2
Intercept	1095.801	1	1095.801	256.340	.000	.774
Intervention Group	0.025	1	0.025	0.006	.939	.000
Error	320.610	75	4.275			

Table 6 shows the descriptive statistics for the motivational measures that were administered to all students.

Table D2

Descriptive Statistics of Motivational Responses

Group	Motivational Measure	N	Minimum	Maximum	Mean	SD
AR-D	Motivation to Engage in Activity	34	.50	5.75	3.4412	1.21552
	Motivation to Engage with AR-D Technology	34	.75	5.75	3.3456	1.10614
Computer Simulation	Motivation to Engage in Activity	32	2.25	5.50	4.0937	.98936
	Motivation to Engage with Computer Simulation Technology	32	1.75	5.75	4.0547	1.02732

Prior to running the MANOVA analysis on the motivational measures, assumptions were checked to assure that the MANOVA test was appropriate. The outcome variables were found to be significantly correlated ($\rho = .877$, $p < .001$). There is a danger that this could be multicollinear as the variance inflation factor is evaluated at 4.331; however, the threshold is often set at a VIF of 5 or above before the collinearity between variables is problematic (James et al., 2013). The data was confirmed to exhibit multivariate normality and Box's M Test showed that the groups can be assumed to have equal covariance matrices (Box's $M = 1.859$, $F = .599$, $p = .616$).