Augmented Reality to Scaffold 2D Representations of 3D Models in Magnetism

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We report on the initial implementation of the MARVLS augmented reality app in three sections of introductory physics courses at Siena College. The courses adopted models with emphasis on the relationship between 2-D and 3-D representations of topics in magnetism. This app is intended to provide engaging and interactive visualizations of abstract concepts. The AR approach has a unique capability to illustrate relationships between physical and mathematical representations. The models were displayed on foam Merge cubes, allowing students to manipulate and explore the 3D representations. The app offers interactive features to control model components, animations, and connections to 2D representations and equations. We compare pre- and post-assessment data and note modest gains for electromagnetism concepts, and in spatial reasoning for the calculus-based physics sections. Further analysis indicates moderate improvement in specific magnetism questions, and a general indication by Likert scale that students found the AR materials helpful to understand magnetism.

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I. INTRODUCTION AND MOTIVATION

We describe a pilot study on the use of a smartphone app to enrich lessons in magnetism, first formally adopted in the spring of 2023 in three introductory physics sections at Siena College. The overall goal of this on-going study is to implement activities that focus on four topics that strongly involve 3D visualization: magnetic field, magnetic force, Ampere's Law, and electromagnetic induction. Implementation involves ensuring ease of student use, development and revision of activities, developing the framework for analysis of student engagement, and the identification of next steps for improvement. This study operates within the guidelines of a human subjects study that requires student anonymity. The classroom activities involve drawing to compare 2D and 3D representations, and answering scaffolded and open-ended questions to investigate models. Analysis includes review of the drawings and activity responses, observing student participation and collecting feedback, assessments, and conducting interviews. The major question is to determine if the models improve student comprehension of abstract concepts that require 3D visualization.

Motivation: 2D to 3D Representations Learning within STEM entails developing robust conceptual understandings and theoretical models involving abstract and complex concepts. Cognitive science is converging on the fact that our understanding of abstract concepts is grounded in embodied experiences and representations [1]. Two critical visuospatial skills critical for learning in STEM are the ability to visualize and manipulate interactions in three dimensions, and the ability to represent and understand these representations in multiple modalities (i.e., representational fluency) [2]. Many cognitive psychologists espouse that poor visuospatial skills represent the true barrier for success in STEM fields [3](and references therein). This barrier may be higher for female students, as spatial reasoning ability is one of the only areas of cognition where a gender difference persists [4]. Spatial reasoning skills can be improved through training courses that develop general spatial visualization skills through different activities including drawing 3D representations [3]. While beneficial, this increases the course load for students with less developed spatial reasoning skills. AR represents a technology that can facilitate spatial reasoning skill development with much lower costs than other technologies such as VR. Recent research has demonstrated that the use of an AR App in addition to traditional instruction in spatial reasoning, led to additional improvements in spatial reasoning, and helped narrow the gender gap in spatial reasoning [5]. However, this still requires students with low spatial reasoning to undertake additional training outside of their typical coursework. An underexplored area of research is whether content specific AR visualizations like those in MARVLS can transfer to gains in domain general spatial reasoning tasks. If so, this would represent a pathway to develop scientists and engineers from underrepresented backgrounds while not requiring additional load on these students.

II. MARVLS: MANIPULABLE AUGMENTED REALITY VISUALIZATIONS TO LEARN SPATIALLY

MARVLS is a smartphone app developed by the first author that uses augmented reality to allow learners to interact with three-dimensional (3D) visualization of concepts in physics courses. The app helps students to develop content knowledge, representational fluency, spatial visualization, and provides opportunities for the co-creation of knowledge within the same activities saving time and making classroom experiences meaningful and impactful. The MARVLS app is available for free on the App Store for iPhones and iPads and on the Google Play Store for Android phones and tablets. QR codes for the app are provided in Figure 1. A link is provided in the app to download and print a paper cube template that can be cut out and assembled. The app includes approximately 80 augmented reality models on topics in electrostatics, circuits, magnetism, induction, optics, mathematics, and several applied physics topics. For more information about the development of the app, refer to presentations and posters given at AAPT and PERC conferences in recent years [6–15].

iOS Android

FIG. 1. QR scannable codes to download the MARVLS app for iOS and Android devices.

III. CLASSROOM USE CASE

The pilot study has so far been conducted in two sections of the calculus-based physics course (n=58) and one section of the life sciences physics course (n=23). We chose to include all available students for this initial stage rather than further splitting this small sample to create a comparison group. The AR content supplements but does not fully replace lecture, problem-solving, reading quizzes and homework. The in-class activities include a paper handout with instructions to navigate to the augmented reality model in the MARVLS app corresponding to each activity. Students are given foam Merge cubes to be used in class [16]. When the student views the model through their smartphone or tablet, they are viewing a digital overlay of the magnetism concept onto one of the sides of the Merge cube. The students hold the Merge cube in their hand allowing the student to rotate the 3D model, change the perspective of the model, and move the model closer or farther away to make the model larger or smaller. In each MARVLS activity, the student is asked to view the model, draw what they see, and answer some questions to further encourage the students to interact with the 3D AR models and bring important aspects of each model to the student's attention. Presently, students work in small teams to answer the activity questions, but they use individual cubes and we collect individual drawings and responses.

The app includes buttons and checkboxes to turn on and off different components in the model, begin or pause an animation, and highlight different components in the model to connect a 2D representation to a component of the 3D model or to link a variable in an equation to a component in the model. A new development in the app is the grey box in the right bottom corner. The purpose is to provide additional ways for the students to make connections between 2D representations and the variables in equations and the 3D models they represent.

An example of one augmented reality model that links a 2D representation of the magnetic field of a current-carrying wire to its 3D AR model is shown in Figure 2. In this model, students can turn on the current (electron model or conventional current model), turn on the magnetic field, and turn on the 2D representation. They can also touch the 2D representation in the grey box on the bottom right. When touched, the arrows in the 3D model turn green to indicate how they correspond to the traditional "dot's and x's" representation indicating vectors out of and into the page.

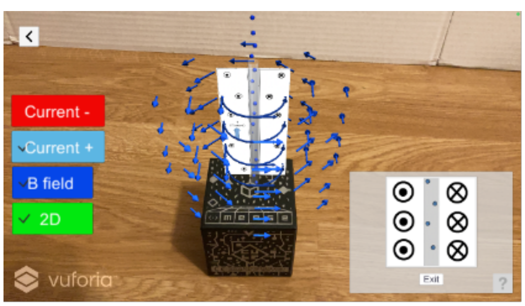

FIG. 2. 2D representation in a 3D AR model of a current-carrying wire and its magnetic field. The 2D picture of wire and field on the bottom right is a button. When the image in the bottom right grey box is touched, the arrows in the 3D model that point out of and into the page are highlighted.

A second example of a MARVLS activity is shown in Figure 3. Two 2D representations of magnetic force on a moving positive charge in a magnetic field are shown on the left. The 3D AR model of the moving charge, magnetic field, and resulting force are shown. The 2D images are added into the model and placed to match with their orthogonal views to match the 3D model.

Student Work To provide some examples of student work, drawings by 4 students are shown in Figure 4. For this activity, students were working with the AR model of the magnetic

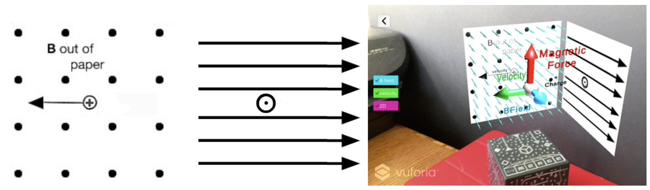

FIG. 3. 2D representations beside a 3D AR model of the force on a moving charge in a magnetic field. The 2D pictures are included in the model to match with their orientations with respect to the 3D model.

field of a current-carrying wire, following the guidelines described in the previous section.

One thing to notice about the student drawings is that each student showed the magnetic field circling the wire. Three of the four students included an indication of the direction of moving charges to represent current. Each of the students drew straight vectors to represent the magnetic field. None of the students drew arrows close to the wire and farther away, so did not notice that the arrows have a smaller length farther from the wire. One student included the 2D representation with dots and x's to represent into and out of the page with his 3D drawing. The student on the bottom left included arrows to represent into and out of the page in his drawing. In a drawing not included here, a student only drew 2D representations - one looking down on the end of the wire and another similar to the picture of the 2D representation in the grey box on the bottom right. However, the student also added 3D arrows to this 2D picture on the left and right to link the dots and x's representing into and out of the page to the arrows in the 3D model. Reviewing student work, these drawings are on the right track, but they are incomplete. As we update the activities, we will incorporate more specific directions to direct student's attention to important details in the AR models. We plan to assess all student drawings, but include these here to indicate the level of progress so far acheived.

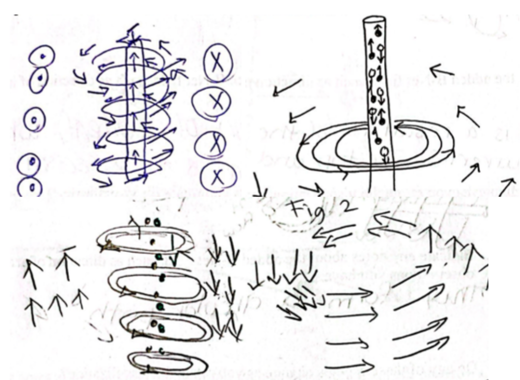

FIG. 4. Student drawings of the 3D AR model of the magnetic field of a current-carrying wire.

IV. ASSESSMENT RESULTS AND DISCUSSION

The initial study has provided much data yet to be analyzed. We are in the process of conducting interviews and reviewing worksheet responses to gain further insights. Here, we examine some assessment results.

In addition to the activities, students complete the Electricity and Magnetism Conceptual Assessment (EMCA) which was developed at Siena College [17, 18]. Students completed The Purdue Visualization of Rotations Test (PVRT) [19]. For the EMCA and PVRT, students completed the assessment at the start and end of the course. The Colorado Learning Attitudes about Science Survey (CLASS) was given once after students completed all of the AR activities [20]. For each question on the EMCA assessment, students were asked to rate through a Likert scale how much using the MARVLS app with the augmented reality models influenced their answer choice. For our human subjects study, the students created a self-identifying ID which they included on the assessments and activities to link the datasets.

Summary of Quantitative Analysis For the quantitative analysis of the impact of the augmented reality models on student learning, we report on the results of the EMCA and PVRT assessments and the CLASS survey. We compared pre and post-test averages for all students, and separately for the calculus-based physics students and the life science physics students. We report normalized gains for these data sets along with standard deviations for each. We also selected the 10 magnetism questions in the EMCA assessment and calculated the average pre-test, post-test, and normalized gains for these 10 questions. Item difficulty scores were calculated for these magnetism questions and item difficulty for these same questions is provided from a previous study by the authors for comparison [17]. The Likert scale results of how the students rated the influence of the AR activities on their answer choice is presented for the 10 magnetism questions. In tables I and II, Calc and Life represents students in the calculus-based and life sciences physics courses respectively.

EMCA Assessment results for the EMCA are given in Table I. The data in this table include the average pretest score, post-test score, and the normalized gain. The equation for the normalized gain is defined as the ratio of the number of points gained between the pre- and post-test divided by the maximum possible gain [21]:

$$\text{normalized gain} = \frac{\text{post-test} - \text{pre-test}}{N_{\text{questions}} - \text{pre-test}}$$

where $N_{\text{questions}}$ is the total number of questions in the assessment. The formula is calculated for each student and the average is reported in the table. Included in Table I are the results of the CLASS survey and the standard deviation. The CLASS results show that student attitudes about science are high as the average is 3 out of a maximum of 5 and above 50%. The EMCA pretest scores for our study are lower than we reported in 2015 and 2016, reflecting a changing demographic at Siena College. The post-test scores were also lower, especially for the calculus-based courses.

Course	n	Pre	STD	n	Post	STD	Gain	STD	CLASS	STD
Calc	33	9.0	3.0	30	14.5	4.8	0.257	0.195	3.1	0.29
Life	22	9.0	2.6	22	11.8	3.8	0.114	0.237	3.0	0.28
All	55	9.0	2.8	52	13.4	4.6	0.190	0.225	3.2	0.28

TABLE I. Average Scores, Normalized Gain Values, and Standard Deviations for EMCA Pre-test, and Post-test for all questions. The EMCA Assessment includes a total of 30 questions and the CLASS survey includes 42 questions.

Course	n	Pre	STD	n	Post	STD	n	Gain	STD
Calc	33	22.2	4.5	30	23.2	4.5	26	0.236	0.41
Life	22	18.2	6.2	20	17.1	7.4	15	-0.663	1.9
All	55	20.2	5.4	50	20.5	6.7	41	-.093	1.2

TABLE II. Average Scores, Normalized Gain Values, and Standard Deviations for Purdue PVRT Pre-test, and Post-test for all questions. The PVRT Assessment includes a total of 30 questions.

PVRT Assessment results for the PVRT are given in Table II. The data in this table include the average pre-test score, post-test score, and the normalized gain. The post-test scores increased with positive gains for students in the calculus-based physics course. The scores decreased for the life science physics students.

Magnetism EMCA questions This analysis focuses on the pre-test and post-test average scores for the magnetism questions in the EMCA assessment. These include questions 21 - 30 [22]. The average scores are included in Table III. For this analysis, the normalized gain was not calculated, however the gain was positive as shown by the increase in post-test score on most questions.

Average number of correct answers for questions 21-30 for the pre-test and post-test are in columns 2 and 3, respectively. Item difficulty for the dataset reported in this paper is in the 4th column and labeled as Difficulty AR and the item difficulty from an earlier source is in the 5th column and labeled Difficulty w/o(without) AR [17]. Average number of students out of 55 that selected Agree or Strongly Agree on the Augmented Reality Likert Score for each problem is in the 6th column. To further explore the impact of the MARVLS

Course Type	n	Avg Pre-test	STD	n	Avg Post-test	STD
Siena Calc-based	33	2.0	1.7	30	4.4	2.2
Siena Algebra-based	22	2.3	1.3	22	3.4	1.5
Siena All	55	2.1	1.5	52	4.0	2.0

TABLE III. AR Magnetism Question Activities: Average Scores and Standard Deviation for pre-test, and post-test for magnetism questions 21 - 30.

activities on student understanding of magnetism topics, we calculated the item difficulty for each of the 10 magnetism questions on the EMCA. The results are show in Table IV. Item difficulty measures the fraction of students that answer the question correctly. The item difficulty is calculated as the number of correct answers divided by the total number of students who took the test:

$$P = \frac{N_C}{N}$$

where P is the item difficulty index, N_C is the number of students that selected the correct answer, and N is the total number of students. Note that a higher value for item difficulty indicates an easier question, while a lower value reflects a harder question. The ideal value for the item difficulty index is 50% for a new assessment [23], but learning should increase the value. The average difficulty index for questions 21-30 is 0.396 with a standard deviation of 0.176. For comparison, the average difficulty index for questions 1-20 is 0.470 with a standard deviation of 0.136. This indicates questions 21-30 on magnetism are more difficult than the first twenty questions covering the concepts of electrostatics and circuits. It is interesting to note that the difficulty decreases (higher values) for questions 26, 29, and 30 suggesting that the MARVLS for those topics likely influenced student understanding of the topics of the magnetic field of a wire and the force on a charge or wire in a magnetic field.

AR Likert Scale The AR Likert values represent the average number of students that took the EMCA post-test and selected agree or strongly agree indicating that the AR activity influenced their answer choice. 52 students took the post-test. Any AR Likert score over 26 indicates that more than half of the students taking the post-test selected agree or strongly agree. The Likert score for problem 21 is shown in Figure 5. It is obvious from the bar chart that more students agreed with the statement that the AR model activity influenced their answer choice for question 21 than students who disagreed or were neutral. This is indicated by the larger value bar for agrees and the large bar for strongly agrees. When compared to questions 1-20, the AR count for questions 21-30 was statistically significantly higher with a p-value of 2.9e-5.

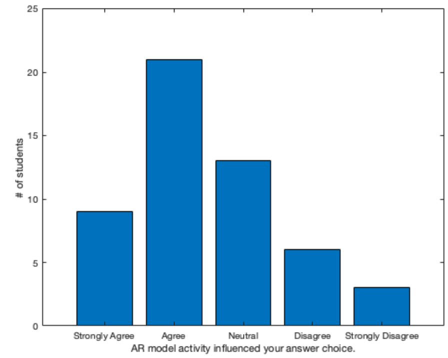

FIG. 5. Likert scale results for students indicating that the AR activity influenced their answer choice for question 21 of the EMCA.

Question	Avg # Pre	Avg # Post	Difficulty AR	Difficulty w/o AR	Avg AR Likert
Q21	8	21	0.40	0.44	30
Q22	12	17	0.33	0.38	30
Q23	19	36	0.69	0.67	32
Q24	5	17	0.33	0.39	32
Q25	9	7	0.14	0.17	26
Q26	7	28	0.54	0.44	27
Q27	15	8	0.15	0.26	23
Q28	5	21	0.40	0.42	27
Q29	23	21	0.58	0.36	26
Q30	14	21	0.40	0.33	26

TABLE IV. Average pretest and post-test EMCA [18, 22] scores, item difficulty index for this study and a prior study [17], and the results of the AR Likert scale values.

V. CONCLUSIONS AND FUTURE WORK

Students in the second semester of introductory physics courses at Siena College completed activities using the MARVLS App where they explored augmented reality models of abstract and 3D concepts that students find difficult. The results of the study indicate that the students engage with the AR models and capture different aspects of the models with their drawings. For the assessment questions on magnetism, the students report that the augmented reality models influenced their answer choices. Gains on the EMCA assessment were modest. The calculus students improved their spatial visualization skills as demonstrated in the PVRT results in Table II. For the calculus students we see evidence for transfer in rotational skills through the use of the MARVLS models, while the difference in PVRT performance for life sciences students warrants further investigation. A speculative reason is the tendency for life science students to utilize rote memorization instead of applying a process.

To continue this work, we will modify the augmented reality activities to highlight the concepts in the model students may have missed without intentional direction. We will also review student work on the activities along with their EMCA scores to understand whether their drawings and answers on the activities correlate with their assessment results. We are conducting interviews with students to understand whether the students believe they benefit from the manipulable AR visualizations. We intend to bring the MARVLS App to a larger audience of colleges and universities and run additional studies to further develop the app and to study the impact of these visualizations on student learning of 3D and abstract concepts in physics. Larger samples will allow for deeper comparisons.

ACKNOWLEDGMENTS

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