Making Magnetism Visible: An NSF IUSE Project Investigating Student Sensemaking with MARVLS Augmented Reality Apps

Michele W. McColgan, Siena University

Dr. Michele McColgan is a Professor in the Department of Physics and Astronomy at Siena University, a small liberal arts institution in upstate New York. She leads the development of Manipulable Augmented Reality Visualizations to Learn Spatially (MARVLS), a suite of augmented reality (AR) smartphone applications designed to enhance physics and engineering education. These tools help students bridge the gap between abstract concepts, 3D models, and the traditional 2D representations and equations found in textbooks. By immersing learners in a visually engaging and interactive environment, the MARVLS apps promote a deeper understanding of complex physics and engineering principles.

Dr. McColgan's research focuses on physics education, investigating how AR technologies influence students' conceptual understanding and spatial visualization skills. Her work explores how manipulating 3D models and linking 2D representations, equations, and real-world phenomena can improve students' comprehension and problem-solving abilities.

George E Hassel, Siena University

George Hassel is a Teaching Professor of Physics and Astronomy at Siena University. He earned a PhD in Physics from Rensselaer Polytechnic Institute as part of the New York Center for Studies on the Origins of Life. Prior to that, he earned a BS in Physics from Widener University with a Secondary Teaching Certificate. His research interests involve the adaptation of inquisition-based and engagement in the undergraduate physics curriculum.

Dr. Kamyar Pashayi, Siena University

Kamyar Pashayi earned a Bachelor of Science degree in Materials Science, a Master's degree in Metallurgical Engineering, and a PhD in Mechanical Engineering. He received his PhD from Rensselaer Polytechnic Institute in Troy, NY in 2012. After graduation, he joined the Department of Mechanical Engineering at Penn State University at Harrisburg as a faculty member, where he was awarded the Research Council Grant. From 2015 to 2020, he worked as an engineer and quality manager in multiple aerospace and pressure vessels manufacturing companies. From 2020 to 2022, he has been a full-time faculty and faculty program director at Excelsior University. Kamyar has been teaching engineering courses at the Applied Physics program at Siena College since 2019 as an adjunct lecturer and now he is rejoining this program as an Associate Professor. Kamyar also holds a MBA degree from University of Albany and he is a licensed professional engineer (PE) in the state of New York. He has multiple journal publications in The Journal of Physical Chemistry, Journal of Applied Physics, Nanoscale, and his current research interests include application of augmented reality in engineering education.

Dr. Jason W Morphew, Purdue University – West Lafayette (College of Engineering)

Dr. Jason Morphew is an assistant professor at Purdue University in Engineering Education and serves as the director of undergraduate curriculum and advanced learning technologies for SCALE, and is affiliated with the INSPIRE research institute for Pre-College Engineering and the Center for Advancing the Teaching and Learning of STEM. Dr. Morphew's research focuses on the application of principles of learning derived from cognitive science and the learning sciences to the design and evaluation of learning environments and technologies that enhance learning, interest, and engagement in STEM. Morphew earned his Ph.D. from the University of Illinois Urbana-Champaign in Educational Psychology from the Cognitive Science of Teaching and Learning Division where he examined self-regulated learning of engineering students enrolled in introductory physics courses.

Making Magnetism Visible: An NSF IUSE Project Investigating Student Sensemaking with MARVLS Augmented Reality Apps

Abstract

The MARVLS Augmented Reality (AR) Apps scaffold students' ability to visualize abstract three-dimensional magnetism concepts and coordinate mathematical expressions with physical representations. Supported by an NSF Improving Undergraduate STEM Education (IUSE) grant, we developed and implemented AR modules in introductory physics courses over three years. Using a mixed-methods approach, we analyzed pre/post conceptual assessments ($n = 144$) and semi-structured interviews ($n = 27$). Results show improved magnetism conceptual understanding and qualitative evidence that AR supports coordination between mathematical and physical reasoning modes. Analysis using the Mathematical Sensemaking (MSM) framework suggests that AR functions as a mediating tool that facilitates translation and coordination across representations. These findings extend prior AR research by identifying mechanisms through which immersive visualization may support conceptual development in undergraduate physics.

Introduction

Understanding abstract, three-dimensional electricity and magnetism (E&M) concepts presents persistent challenges for undergraduate STEM students. Mastery requires students to visualize invisible vector fields, mentally rotate 3D structures, connect two-dimensional diagrams to spatial models, and interpret variables in mathematical expressions as physical quantities [1-3]. Traditional representations such as static diagrams, symbolic notation, and equations may not provide the dynamic, embodied experiences needed to support coordination across representations.

Augmented reality (AR) has emerged as a promising tool for enhancing spatial reasoning and engagement in physics and engineering education [4-10]. By allowing learners to manipulate 3D models anchored to physical objects, AR environments may reduce cognitive load associated with coordinating multiple representations.

The MARVLS mobile app, used with a Merge© cube, overlays interactive 3D magnetism models onto a physical target through a smartphone camera. Students rotate and reposition the cube while selectively displaying equations, vectors, and coordinate axes. For example, in the Lorentz force scene, students visualize velocity, magnetic field, and force vectors alongside the corresponding equation, directly linking symbolic and physical representations (Figure 1). Prior work has examined individual MARVLS magnetism scenes and documented how AR supports gesture use, representational fluency, and conceptual reasoning in magnetism contexts [11-15].

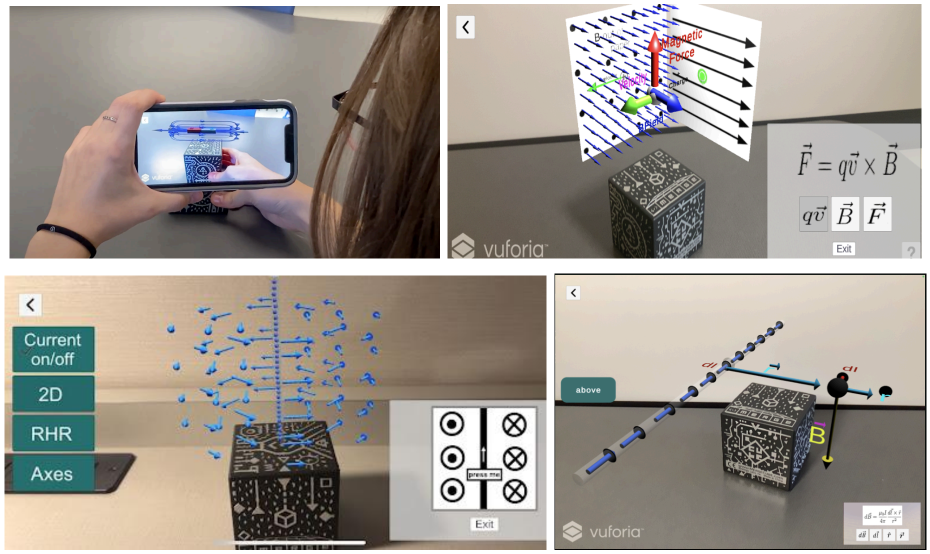

Figure 1. Examples of the AR Scenes as viewed through the smartphone screen for four magnetism scenes: the magnetic field of a magnet, the Lorentz force on a moving charge in a magnetic field, the magnetic field of a current-carrying wire, and the Biot-Savart Law.

In this paper, we synthesize analyses of student reasoning across five magnetism topics: the magnetic field of a wire, the Biot–Savart law, the right-hand rule (RHR), the Lorentz force, and electromagnetic induction, using the Mathematical Sensemaking (MSM) framework [16–19].

Theoretical Framework: Mathematical Sensemaking (MSM)

The MSM framework characterizes how learners coordinate mathematical and physical tools and objects during problem solving. It distinguishes four reasoning modes based on whether mathematical or physical tools mediate interaction with mathematical or physical objects. Productive reasoning involves translation (shifting tools or objects), chaining (sequencing reasoning structures), and coordination. Figure 2 illustrates the four reasoning modes in the MSM framework and the coordination process that leads to a “molecule of sensemaking.”

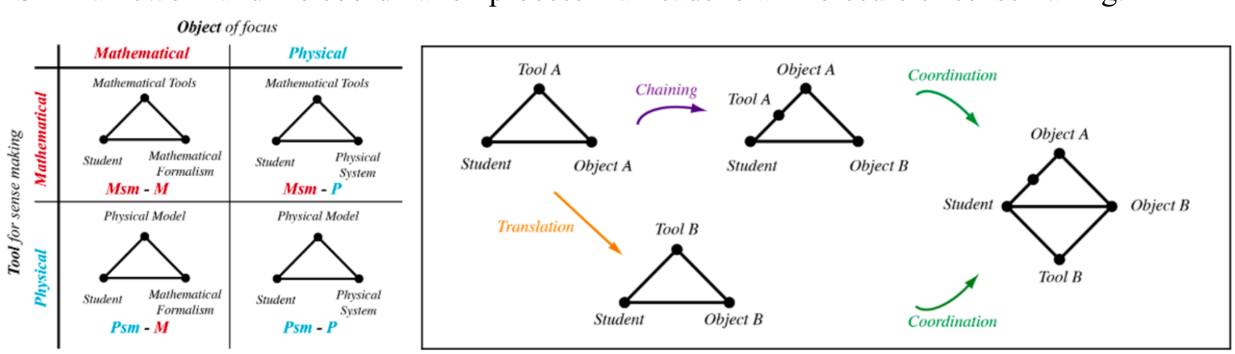

Figure 2. Left: the four modes of the MSM framework, defined by the tool and the object of sense-making. Right: a sense-making diagram, showing the processes of translation and coordination that lead to a coordinated reasoning structure called a “molecule of sensemaking”.

In AR environments, physical manipulation of a 3D model may function as a mediating tool that supports translation between mathematical expressions and physical interpretations. Prior applications of the MSM framework to MARVLS AR models have examined student reasoning in contexts including 3D vectors, the Lorentz force, and electromagnetic induction [11–13]. The present paper integrates findings from these studies to characterize how AR supports coordination across magnetism topics. We address the following research questions:

RQ1: To what extent are gains in conceptual understanding of magnetism observed following interaction with MARVLS AR models?
RQ2: How do students coordinate mathematical and physical reasoning modes while interacting with AR models, as characterized by the Mathematical Sensemaking (MSM) framework?

Methodology

The NSF-supported project employed a mixed-methods design examining students' reasoning while interacting with MARVLS AR magnetism models.

Participants

The study included 144 students enrolled in introductory physics courses at a small private liberal arts institution in the northeastern United States. Participants were drawn from four sections of an algebra-based life sciences course (PHYS 120, $n = 67$) and three sections of a calculus-based course for physics and mathematics majors (PHYS 140, $n = 77$) during 2024–2025. Twenty-seven students participated in semi-structured interviews. Sixteen interviewees were enrolled in physics courses following AR implementation; eleven were introductory psychology students who had not taken college-level physics. Approximately 56% identified as women and 44% as men.

Data Collection and Analysis

Conceptual understanding was assessed using the Electricity and Magnetism Conceptual Assessment (EMCA) [20] administered pre- and post-instruction. Interviews guided students through AR interactions across five magnetism topics. Interview transcripts were analyzed using the MSM framework to identify translation, chaining, and coordination across reasoning modes.

Results

Quantitative Results

EMCA scores improved from pretest to posttest in both courses (Table 1). PHYS 140 students demonstrated higher normalized gains ($g = 0.27$) than PHYS 120 students ($g = 0.18$).

Additionally, 34% of PHYS 140 students and 16% of PHYS 120 students achieved posttest scores ≥18, a threshold indicating entry into E&M reasoning.

Table 1. EMCA Assessment Results (correct out of 30 questions)

Course	No. of students	Pretest (average)	Posttest (average)	Hake normalized gain (average)	No. of students with posttest score >=18
PHYS 120	67	9.4	13.1	0.1782	11 (16%)
PHYS 140	77	10.0	15.4	0.270	26 (34%)

These gains occurred in courses that also incorporated active-learning strategies; thus, results reflect implementation within an interactive instructional context.

Qualitative Results

Building on prior qualitative analyses of MARVLS magnetism scenes [11–14], this paper integrates findings across topics using the MSM framework. Interview analysis revealed that AR interactions supported coordination between physical gestures, 3D visualizations, and symbolic representations. While interacting with the Lorentz force scene, one student rotated the cube, aligned his RHR gesture with the AR vectors, and displayed the Lorentz force equation before stating, “v is my pointer and that’s to the left, B is my middle finger and that’s toward me, and F is the answer and that’s my thumb.” This moment reflects coordination between physical manipulation of the AR model (Psm-P), embodied gesture (Psm-P), and interpretation of the mathematical structure (Msm-P), consistent with coordinated reasoning across modes (Figure 2). Similarly, another student explained, “I used to just memorize the right-hand rule, but now I can see why it works,” illustrating translation from procedural recall to conceptual reasoning.

Across interviews, students rotated the 3D model, aligned it with 2D diagrams, referenced equations, and applied RHR gestures. When later asked to explain concepts without the app, many reported mentally visualizing the AR model while gesturing, suggesting internalization of spatial representations. One student explained, “After I really developed that link between the picture, the model, and the equation, I didn’t need to use the cube itself because I could picture it in my head. Now, anytime I see a wire, I imagine the model on the Merge cube and turn it to see how the magnetic field curls.” This account suggests that the AR environment functioned as a mediating tool appropriated beyond the immediate interaction, reflecting sustained coordination across mathematical and physical reasoning modes.

Students also described how the AR model reduced what one participant called the “fuzziness” of 3D magnetism concepts. Without the cube, he could “only plug numbers into the equation” but struggled to clearly picture the phenomenon. With the AR model, “there’s no fuzziness because the picture's right there." He further noted that he could manipulate the cube "to get that 2D representation and fully understand what that graph is saying," rotating the model to match projected views. These accounts suggest that AR supports representational fluency by reducing the cognitive burden of mental rotation and enabling coordination between equations, diagrams, and spatial models.

Discussion and Conclusion

Prior research on AR in physics education reports gains in spatial reasoning and engagement [4–9]. Our findings are consistent with this literature and further contribute by analyzing how AR mediates transitions between mathematical and physical reasoning modes using the MSM framework. The observed gains in conceptual understanding, together with qualitative evidence of coordinated reasoning, suggest that AR-supported interaction may facilitate deeper integration of mathematical and physical representations. The AR environment functioned as a hybrid mediating tool, enabling translation between vector equations and 3D field representations. MSM analysis suggests that AR scaffolds coordination across reasoning structures, supporting development of coherent "molecules of sensemaking."

Implications

For instructors, AR modules that explicitly highlight variable-to-vector correspondences may strengthen representational fluency. For curriculum designers, embedding dynamic feedback mechanisms may promote productive chaining and translation across representations. More broadly, immersive visualization tools may support spatial reasoning skills critical to STEM persistence.

Limitations and Future Work

This study was conducted at a single institution without a control group, and courses incorporated active-learning strategies that may also contribute to observed gains. Future work should include multi-institutional implementations and controlled comparisons to further isolate the impact of AR-mediated reasoning.

Acknowledgements

This material is based upon work supported by the National Science Foundation under grant #2120446. The authors thank the Siena University instructors and students who participated in this study.

References

[1] P . B. Kohl and N. D. Finkelstein, “Student representational competence and self-assessment when solving physics problems”, Phys. Rev. ST Phys. Educ. Res. vol. 1, 2005.

[2] M. Sağlam and R. Millar, “Upper High School Students’ Understanding of Electromagnetism,” Int. J. Sci. Educ., vol. 28, no. 5, pp. 543–566, Apr. 2006, doi: 10.1080/09500690500339613.

[3] Bennett, J. A., & Morphew, J., & McColgan, M. W. (2024, June), Embodied Learning with Gesture Representation in an Immersive Technology Environment in STEM Education Paper presented at 2024 ASEE Annual Conference & Exposition, Portland, Oregon. 10.18260/1-2--47233

[4] J.E. Bell, C. Cheng, H. Klautke, W. Cain, D.J. Freer, and T.J. Hinds, “A study of augmented reality for the development of spatial reasoning ability” in 2018 Annual Conference & Exposition, Salt Lake City, UT, June 24-27, 2018.

[5] J.E. Bell, T. Lister, S. Banerji, and T.J. Hinds, “A study of an augmented reality app for the development of spatial reasoning ability” in 2019 Annual Conference & Exposition, Tampa, FL, June 2019.

[6] E. Davishahl, T. R. Haskell, J. Davishahl, L. Singleton, and W.H. Goodridge, “Do they understand your language? Assess their fluency with vector representations”, in 2019 Annual Conference & Exposition, Tampa, FL, June 2019.

[7] Cai, S., Chiang, F. K., Sun, Y ., Lin, C., and Lee, J. J., “Applications of augmented reality-based natural interactive learning in magnetic field instruction”, Interactive Learning Environments, vol. 25, issue 6, pp. 778-791, 2017, doi: 10.1080/10494820.2016.1181094

[8] Fidan, M., and Tuncel, M., “Integrating augmented reality into problem based learning: The effects on learning achievement and attitude in physics education”, Computers and Education, vol. 142, p. 103635, 2019, doi:10.1016/j.compedu.2019.103635

[9] Lai, J. W., and Cheong, K. H., “Educational opportunities and challenges in augmented reality: Featuring implementations in physics education”, IEEE Access, vol. 10, pp. 43143-43158, 2022, doi: 10.1109/ACCESS.2022.3166478

[10] C.H. Godoy, Jr, “A Review of Augmented Reality Apps for an AR-Based STEM Education Framework”, Southeast Asian Journal of STEM Education, V ol 3, No. 1, Jan. 2022, doi:

10.48550/arXiv.2203.07024

[11] McColgan, M., & Hassel, G. E., & Pashayi, K., & Morphew, J., & Bennett, J. A. (2025, June), MSM Framework: Augmented Reality Models of 3D Vectors Paper presented at 2025 ASEE Annual Conference & Exposition , Montreal, Quebec, Canada . 10.18260/1-2--56981

[12] M. W. McColgan, G. E. Hassel, and K. Pashayi, MSM Framework: AR Model of the Force on a Charge Moving in a Magnetic Field, 2024 PERC Proceedings [Boston, MA, July 10-11, 2024], edited by Q. X. Ryan, A. Pawl, and J. P. Zwolak, doi:10.1119/perc.2024.pr.McColgan.

[13] M. W. McColgan, G. E. Hassel, K. Pashayi, and J. W. Morphew, "Seeing Electromagnetic Induction: Student Sense Making with Augmented Reality," Proceedings of the 2026 ASEE Annual Conference, 2026 (accepted).

[14]M. W. McColgan, J. W. Morphew, G. E. Hassel, J. A. Bennett, and M. C. Kelly (2024, June), Board 415: Understanding Magnetism Concepts Through Augmented Reality: A Qualitative Analysis, Paper presented at 2024 ASEE Annual Conference & Exposition, Portland, Oregon. 10.18260/1-2--47004

[15] M. W. McColgan, G. E. Hassel, N. C. Stagnitti, J. W. Morphew, and R. S. Lindell, Augmented Reality to Scaffold 2D Representations of 3D Models in Magnetism, 2023 PERC Proceedings [Sacramento, CA, July 19-20, 2023], edited by D. L. Jones, Q. X. Ryan, and A. Pawl, doi:10.1119/perc.2023.pr.McColgan.

[16] Gifford, J., & Finkelstein, N. (2021, May 24). Applying a mathematical sense-making framework to student work and its potential for curriculum design. Phys. Rev. Phys. Educ. Res., 17(1), 010138. https://doi.org/10.1103/PhysRevPhysEducRes.17.010138

[17] Gifford, J., & Finkelstein, N. (2020, September 22). Categorical framework for mathematical sense making in physics. Phys. Rev. Phys. Educ. Res., 16(2), 020121. https://doi.org/10.1103/PhysRevPhysEducRes.16.020121

[18] Gifford, J., & Finkelstein, N. (2020, July 22-23). A framework for curriculum design to support mathematical sense making. Paper presented at Physics Education Research Conference 2020, Virtual Conference. https://www.compadre.org/Repository/document/ServeFile.cfm?ID=15479&DocID=5327

[19] Gifford, J., & Finkelstein, N. (2019, July 24-25). Categorizing mathematical sense making and an example of how physics understanding can support mathematical understanding. Paper

presented at Physics Education Research Conference 2019, Provo, UT. https://www.compadre.org/Repository/document/ServeFile.cfm?ID=15273&DocID=5184

[20] M. McColgan, R. Finn, D. Broder, and G. Hassel, Assessing students' conceptual knowledge of electricity and magnetism, Phys. Rev. Phys. Educ. Res. 13 (020121), (2017), <https://doi.org/10.1103/PhysRevPhysEducRes.13.020121>.