AR/VR for Enhancing Conceptual Understanding and Learning in Electromagnetics

Dr. Meghan Mcglinn Manfra, North Carolina State University

Dr. Meghan McGlinn Manfra is a Professor of Social Studies Education in the Department of Teacher Education and Learning Sciences at North Carolina State University. Her research examines how inquiry, reflection, and technology enhance teaching and learning across disciplines, with a focus on immersive and responsible technology integration in education. She collaborates with colleagues in Electrical and Computer Engineering to design and evaluate augmented and virtual reality (AR/VR) learning environments that improve conceptual understanding in electromagnetics.

Dr. Manfra also serves as an evaluator for several large-scale NSF-funded initiatives, including the ASSIST Engineering Research Center (ERC), AccelNet: Broadening Carbon Ring Network of Networks, and multiple Research Experiences for Undergraduates (REU) programs. Through this work, she studies how interdisciplinary, experiential, and international research experiences build students' skills and confidence in STEM fields. In addition, she collaborates with the Data Science and AI Academy at NC State to advance responsible and ethical approaches to artificial intelligence education. She is the author of Action Research for Classrooms, Schools, and Communities (SAGE, 2019) and the forthcoming Fighting Fake News for Teens and Adolescents (Bloomsbury, 2025).

Dr. David S. Ricketts, North Carolina State University at Raleigh
Michael Prelaske, North Carolina State University at Raleigh
Arman Afsari, North Carolina State University at Raleigh

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Meghan Manfra Professor, Department Teacher Education and Learning Sciences, NC State University (mmmanfra@ncsu.edu)

Mike Prelaske Graduate Research Assistant, Department of Teacher Education and Learning Sciences, NC State University (mprelas@ncsu.edu)

Arman Afsari, Assistant Research Professor, Department of Electrical and Computer Engineering, NC State University (aafsari@ncsu.edu)

David Ricketts Professor, Department of Electrical and Computer Engineering, NC State University (dricket@ncsu.edu)

Using Augmented Reality for Enhancing Conceptual Understanding and Learning in Electromagnetics

This paper is a Work in Progress (Empirical Research) that explores the use of augmented reality (AR) applications to enhance undergraduate students' conceptual understanding of electromagnetics (EM) in electrical engineering and physics courses.

Motivation/Problem: The field of electromagnetics is among the most conceptually demanding in engineering education, requiring students to reason about abstract, unseen phenomena such as electric and magnetic fields, vectors, and superposition. Traditional instruction emphasizes mathematical formulas and vector calculus over spatial reasoning and conceptual understanding, leading to persistent misconceptions and low student self-efficacy. This project addresses the need to leverage emerging technologies such as augmented and virtual reality to provide more intuitive and engaging tools to support students; in this case, to support undergraduate students in visualizing and interacting with complex three-dimensional relationships central to an understanding of electromagnetics.

Conceptual Framework: Our study draws from the extant research literature on experiential learning and embodied cognition theories to guide the design of interactive AR learning environments. We hypothesize that physical interaction and spatial exploration within immersive environments promote conceptual change and deeper understanding of electromagnetic relationships. In this case, we designed a series of AR modules to scaffold learning while aligning directly with core electromagnetic curriculum objectives.

Methods: The research team developed a series of eight AR modules, accessible through a software application (app) "Visualize Physics AR" loaded on mobile devices, to help students visualize the following: 1. Vector fields, 2. Electric fields, 3. Superposition, 4. Linear and surface charges, 5. Electric potential 6. Gause's Law, 7. Conductors and dielectrics, 8. Force and energy. As students proceeded through the modules they received haptic feedback to scaffold their visual exploration of key concepts and virtual manipulation of objects (e.g., arrows to represent vector fields].

In Fall 2025 we piloted the use of the app in an undergraduate course "Electromagnetic Fields" offered by the ECE department at a major research institution. We recruited student participants to test the app and to provide feedback. We also collected pre- and post-[quantitative] data from the students to gauge their user experiences as well as any potential growth in their conceptual knowledge. The data collected and feedback received from the student participants and faculty during the fall semester informed the methodology that is currently being implemented to gauge the effectiveness of the app on student outcomes during the spring semester.

The spring study employed a sequential explanatory mixed-methods design combining a randomized controlled experimental component with post-intervention qualitative interviews. The quantitative phase examined the causal impact of augmented reality instructional modules on undergraduate engineering students' content mastery, while the qualitative phase explored students' learning experiences and mechanisms underlying observed performance differences.

The experimental component consisted of four repeated randomized trials ("waves") embedded within a single semester of an undergraduate Electrical and Computer Engineering (ECE) course. Each wave aligned with a distinct pair of instructional modules. Quantitative findings informed the sampling and focus of the qualitative interviews conducted following module completion. We chose to use this segmented approach to reduce the burden on individual students since the testing was done outside of regular course time. This approach was also attractive in that it warranted both cross-case and cross-comparison approaches to analyze the data.

Participants were recruited from an undergraduate ECE course enrolling 189 students at a large public university. All students were invited to complete a voluntary demographic and background survey prior to the experimental phase. Sixty-two students (32.8%) completed the survey and constituted the initial recruitment pool. From this pool, participants were recruited in groups of 20 students per wave, yielding a planned experimental sample of 80 students across four waves. Participation in the experimental study was voluntary and did not affect course grades beyond normal assessment procedures.

The experimental intervention was implemented across four instructional waves corresponding to paired course modules (see appendix A). Each wave followed an identical procedure to ensure consistency and internal validity.

Pre-Assessment: At the beginning of each wave, all 20 participants completed a module-aligned pre-assessment designed to measure baseline conceptual understanding relevant to the instructional content. Pre-assessments consisted of instructor-validated items aligned directly with course learning objectives for the relevant modules. Following pre-assessment, participants were randomly assigned to one of two conditions: 1) Experimental group ($n = 10$): completed the AR instructional modules and 2) Control group ($n = 10$): did not receive the AR intervention. Randomization was conducted within each wave using blocked random assignment to ensure equal group sizes. Random assignment occurred after pre-assessment to avoid expectancy effects. Assignment procedures were documented and applied consistently across all waves.

Intervention Condition: Students in the experimental condition completed AR modules designed to support spatial reasoning, visualization, and conceptual understanding of core engineering concepts. Modules were accessed individually and completed within a defined time window aligned with course pacing. Usage data, including time-on-task and completion status, were recorded where available to support secondary analyses of engagement and dosage.

Control Condition: Students in the control condition received standard instruction only ("business-as-usual"), consisting of lectures, course materials, and non-AR study resources typically provided in the course. Control participants did not access AR content during the intervention window.

Primary Quantitative Outcome: The primary outcome measure was performance on midterm examination items aligned with the relevant instructional modules. Each midterm item was mapped to specific module content using an instructor-validated item alignment matrix.

Secondary Quantitative Outcome: A secondary outcome measure was overall midterm examination performance, used to examine whether localized learning gains generalized to broader course assessments.

Qualitative Phase: In addition to field notes collected during the intervention, approximately 5-10 interviews were conducted across the four waves to understand student experiences using the app. This included both the technical and logistical issues related to using the app as well as the student perceptions about the relevant benefits of using the app for learning. We hope that by conducting post-interviews we could gather student feedback after they had a chance to compare the app content to course content as well. Findings from the qualitative phase were integrated with quantitative results using joint displays linking assessment outcomes with thematic patterns. This integration supported interpretation of observed performance effects by identifying mechanisms through which AR influenced learning, as well as conditions under which the intervention was more or less effective.

Validity Considerations: Potential threats to internal validity, including selection effects and contamination between groups, were mitigated through random assignment, standardized procedures across waves, and post-intervention self-report measures assessing indirect exposure to AR content. However it was beyond the scope of this current project to identify matched sets based on criteria other than course enrollment (other factors for comparison such as gender, ethnic background, academic achievement could be considered in future studies).

Participants: Across both the Fall 2025 pilot and the Spring 2026 study, a total of 79 students consented to participate (n = 23 in Fall 2025; n = 56 in Spring 2026). Participants were predominantly male (Fall: 17 male, 4 female, 2 prefer not to answer; Spring: 44 male, 10 female, 1 prefer not to answer) and ranged in age from 18 to 30, with the majority (88% in Spring 2026) falling between 18 and 23 years old. Nearly all participants were advanced undergraduates, with 49 of 56 Spring participants (87.5%) having completed 41 or more credit hours toward their degree. Participants were overwhelmingly enrolled in Electrical Engineering or Electrical and Computer Engineering programs, consistent with the target population for ECE 303.

Findings: The data collected and analyzed during both the Fall and Spring suggested that the AR/VR experiences improved students' ability to visualize electromagnetic fields. Prior to the intervention, Spring 2026 participants reported moderate familiarity with course concepts on a 5-point scale. Self-reported familiarity was highest for Force and Energy (M = 3.20) and lowest for Linear and Surface Charges (M = 2.16) and Gauss's Law (M = 2.21), reflecting expected gaps in prior exposure to electromagnetics content (Appendix D). Students reported moderate familiarity with AR/VR technologies (M = 2.96), suggesting the sample was neither highly experienced nor completely unfamiliar with the modality. Notably, 70% of consented Spring participants (39 of 56) rated visualization as a 4 or 5 out of 5 for helping them learn; providing strong baseline support that students themselves recognized the potential value of visual tools for understanding equations and abstract concepts. The large majority of participants (47 of 56, 84%) preferred in-person learning environments.

Following participation in the AR intervention sessions, students completed brief module-aligned assessments (scored out of 10) designed to measure conceptual understanding of the content covered in each paired module wave. Due to the voluntary and staggered nature of wave participation, sample sizes per wave were small, and these results should be interpreted as descriptive and preliminary. Mean scores across waves ranged from 3.50 (Modules 3–4: Superposition and Linear/Surface Charges, $n = 4$) to 4.60 (Modules 7–8: Conductors, Dielectrics, Force and Energy, $n = 5$), with Modules 1–2 (Vector Fields and Electric Fields, $n = 8$) yielding a mean of 4.25 and Modules 5–6 (Electric Potential and Gauss's Law, $n = 3$) yielding a mean of 4.00 (Appendix C). The modest scores across waves are consistent with the high conceptual difficulty of the content and the early-in-semester timing of assessments, and do not reflect post-instruction performance.

The primary quantitative outcome for the Spring 2026 cohort was performance on the course midterm examination ($n = 23$). Students who attended the AR intervention session ($n = 9$) earned a mean midterm score of 84.7 ($SD = 15.2$), compared to a mean of 77.5 ($SD = 13.8$) for students who did not attend ($n = 14$), representing a 7.2-point difference. An independent-samples t-test indicated that this difference was not statistically significant ($t = 1.17$, $p = 0.26$), However, the effect size was moderate (Cohen's $d = 0.50$), suggesting a practically meaningful difference that the study was underpowered to detect at conventional significance thresholds given the small sample. The overall cohort mean midterm score was 80.3 (range: 52–99)(Appendix B)

These findings are consistent with patterns reported in the pilot phase, in which students who participated in both rounds of app testing also outperformed peers on in-class assessments. Taken together, the quantitative data across both semesters suggest a promising, if not yet statistically confirmed, positive association between AR engagement and midterm performance. The moderate effect size ($d = 0.50$) is noteworthy and warrants continued investigation with larger samples, as it falls within the range typically considered educationally meaningful in intervention research.

Qualitative findings: Students reported being able to better connect the abstract mathematical formulas to the virtual experiences using the app. For example, students seemed to value the visualization of abstract concepts and reported that the tools helped them “see” how positive and negative charges interact and how forces vary with distance. Many linked the experiences using the app to prior knowledge from physics courses and described the visualization as a “good way to understand what’s happening.” However, technical and usability barriers were also reported. Despite moments of frustration, students described the app as an “efficient mode for teaching” and recommended that it be integrated earlier in the engineering curriculum to support gatekeeper courses.

Implications and Future Work: This work-in-progress contributes to the growing body of research on AR/VR in engineering education by demonstrating how immersive tools can strengthen student conceptual understanding in electromagnetics and related STEM domains. In contrast to previous AR/VR work that emphasize engagement or novelty effects, this project explicitly targets persistent conceptual challenges related to vector field visualization, superposition, and spatial reasoning, aligning immersive design features with core disciplinary learning objectives. Preliminary findings suggest that AR-supported visualization may help close a well documented gap between mathematical formalism and physical intuition within engineering education. Student reports of being better able to “see” field interactions and relate this to prior physics content knowledge suggests that AR can serve as a concept mediator - creating a bridge for students to form new understandings.

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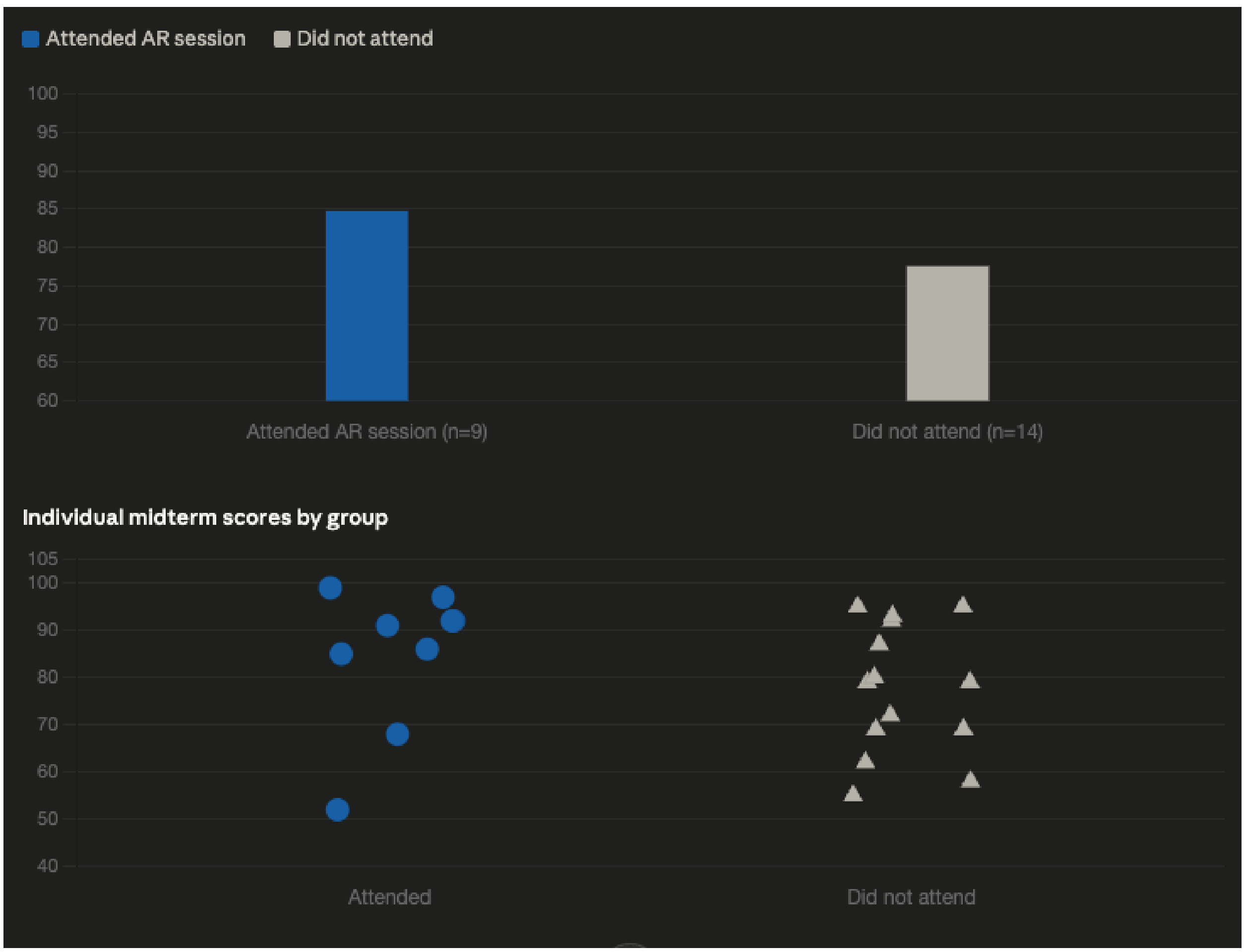
Appendices

Appendix A

Experimental intervention (Spring 2026)

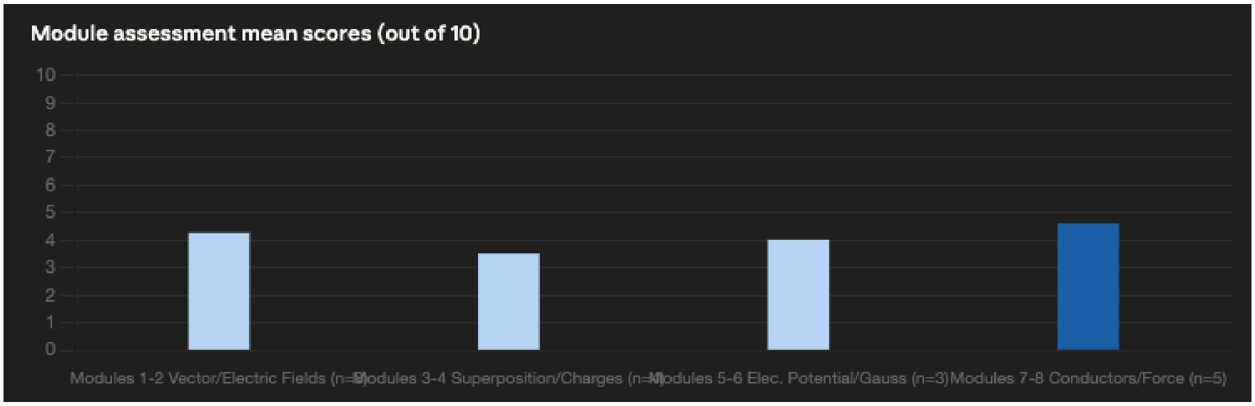
Wave 1	Modules 1-2		Vector fields, 2. Electric fields,
Wave 2	Modules 3-4		Superposition, 4. Linear and surface charges,
Wave 3	Modules 5-6		Electric potential 6. Gause's Law,
Wave 4	Modules 7-8		Conductors and dielectrics, 8. Force and energy

Appendix B
2026 Spring Midterm Scores



Appendix C

Module Assessment Mean Score (Spring 2026)



Appendix D

Prior Concept Familiarity (Spring 2026)