

Voice-Driven Conversational Mixed Reality for Linear Algebra in Computer Science Education Using an AI Avatar Tutor*

Sheldon Henriques¹, Abbas Attarwala, Ph.D.¹,
and Ed Lindoo, Ph.D.²

¹Computer Science Department
California State University
Chico, CA, 95973

svhenriques@csuchico.edu, aattarwala@csuchico.edu

²Computer Information Systems
Anderson School of Business
Regis University
Denver, CO, 80221
elindoo@regis.edu

Abstract

This paper presents an advanced mixed reality (MR) application that integrates conversational artificial intelligence (AI) with voice-driven mathematical visualization for linear algebra education in computer science (CS) courses. Building upon previous work in MR-based mathematical learning, our system introduces a virtual Albert Einstein avatar that students can interact with through natural language commands to create, manipulate, and explore mathematical concepts in Meta Quest 3s. Students can verbally request vector and plane generation, perform vector operations, and execute step-by-step Reduced Row Echelon Form (RREF) algorithms through conversational interaction with the

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AI avatar. Another contribution of this work is the integration of real-world astronomical visualizations, where students can observe how rotational matrices control the Earth’s rotation, the Moon’s rotation, and the Moon’s orbital motion around Earth, providing tangible context for abstract linear transformation concepts in linear algebra. This voice-driven approach addresses different learning modalities compared to traditional hand-tracking interfaces, enabling students to focus on conceptual understanding rather than manual manipulation. The preliminary evaluation among first-year students demonstrates enhanced engagement and comprehension, particularly for auditory learners who benefit from the conversational interaction model. The system represents a significant advancement in multimodal educational technology, combining the immersive benefits of MR with the accessibility of natural language interaction and the pedagogical advantages of AI-assisted tutoring for complex mathematical concepts.

1 Introduction

Linear algebra serves as a foundational course for students of mathematics and engineering, but its abstract nature presents significant pedagogical challenges [9]. Traditional classroom instruction relies heavily on symbolic manipulation and two-dimensional representations, leaving many students struggling to develop an intuitive understanding of concepts that are inherently three-dimensional. Our recent work [4] has demonstrated the potential of MR for mathematical visualization. Our previous research shows that interactive 3D environments can effectively support linear algebra learning through hand-tracking and controller-based manipulation of vectors, planes, and geometric visualization of the RREF process. Although this initial work successfully demonstrated that MR visualization enhances comprehension, particularly for visual and kinesthetic learners, it relied primarily on manual interaction modalities that still required students to navigate complex interfaces and controller mechanisms. Building upon these findings, this paper introduces a fundamentally different approach that integrates conversational AI with voice-driven mathematical visualization. Conversational agents using natural language interactions have been shown to significantly reduce anxiety toward mathematics among students [10]. Natural language interaction mirrors the way humans naturally process and communicate mathematical ideas, allowing students to articulate their thinking, ask questions spontaneously, and receive immediate feedback in a familiar format. When students can verbally request “generate two planes that intersect on a line” or “generate three planes that intersect on a point” or “show me how this rotation matrix affects the Earth’s motion,” they engage with mathematics as a dialogue rather than a series of mechanical

operations. This conversational approach reduces the cognitive load by eliminating the need to navigate complex interfaces, allowing students to focus entirely on conceptual understanding, a limitation identified in our previous work, where students occasionally struggled with controller sensitivity and navigation complexity. The integration of a virtual Albert Einstein avatar represents a strategic pedagogical choice that extends beyond our previous work’s focus on geometric visualization. Animated pedagogical agents (PA) that utilize real-time rendering and anime-style esthetics can mitigate the uncanny valley effect, resulting in more natural and comfortable interactions, as demonstrated by significantly higher user preference ratings compared to realistic talking-head approaches [2]. Such systems show potential to increase student engagement and improve learning outcomes through adaptive, on-demand support, and personalized feedback [2]. The avatar serves not only as an interface, but as a virtual mentor who can guide students through their mathematical journey with personality and context, addressing the need for more intuitive interaction identified in our initial pilot study feedback. However, the true innovation lies in the multimodal learning experience that seamlessly combines voice interaction with the proven benefits of physical manipulation demonstrated in our previous work. After students use voice commands to generate mathematical objects through conversation with Einstein, they can transition to manipulating these objects with their hands and controllers—leveraging the successful hand-tracking capabilities established in our initial application. As students physically adjust a plane’s orientation or modify a vector’s direction, Einstein’s avatar provides real-time feedback, verbalizing the new equations, and explaining the mathematical implications of their actions. This creates a continuous loop of conversation, visualization, and tactile manipulation that addresses multiple learning modalities simultaneously, based on our previous finding that the combination of visual and kinesthetic interaction significantly enhances student comprehension. While our previous work [4] focused on the visualization of fundamental concepts such as vector addition, span, and RREF visualization, this new application also extends into advanced linear algebra applications through real-world astronomical visualizations. By engaging multiple senses and interaction modalities simultaneously, students can construct understanding through their preferred learning channels while being exposed to alternative approaches that strengthen their overall comprehension. The result is a learning environment that transforms abstract linear algebra into an interactive, conversational, and deeply engaging experience that addresses the usability concerns identified in our initial pilot study while dramatically expanding the scope of mathematical concepts that can be effectively visualized and manipulated in MR environments.

2 Literature Review

The IllusionX system by [12] proposes integrating conversational AI with MR technologies for academic support, providing a conceptual framework for our AI Avatar Tutor approach. Although its MR components remain untested, their system architecture demonstrates how LLM can be combined with immersive interfaces, and their evaluation of LLM-based educational tasks showed marginal improvements in generating coherent course content when leveraging knowledge embedding. The affective computing capabilities of IllusionX validate the pedagogical potential of MR-based conversational interfaces to increase engagement and personalize learning in mathematical education.

The systematic review by [5] analyzing 66 studies from 2015 to 2023 demonstrates that AR significantly improves mathematical creativity, student motivation, and spatial understanding. Their findings show that AR applications promote active learning by combining physical objects with digital simulations, particularly effective for visualizing abstract mathematical concepts. These insights directly support our Avatar Tutor system, which combines MR visualization with conversational AI to address linear algebra’s cognitive challenges through multimodal engagement.

[6] examines the integration of Intelligent Tutoring Systems within AR and VR environments, demonstrating that this combination creates effective immersive learning environments that support personalized education. These systems identify, monitor, and adapt to the characteristics of the students while providing tailored real-time feedback. Students in such environments demonstrate increased engagement, motivation, and improved knowledge retention, directly supporting our Avatar Tutor approach that combines conversational AI with MR visualization.

[8] compared the effectiveness of ChatGPT-generated mathematics hints with human-authored hints in a randomized study with 274 participants in four math topics (Elementary Algebra, Intermediate Algebra, College Algebra, and Statistics). Participants were assigned to one of three conditions: no hints (control), human tutor hints, or ChatGPT hints. The results showed that the ChatGPT hints produced a 17% learning gain that was statistically significant compared to the control group’s 1.85% gain. The human tutor hints yielded an 11.62% gain, but this difference from the control was not statistically significant. Importantly, there was no statistically significant difference between the ChatGPT and the human tutor conditions, suggesting that ChatGPT performed similarly to human-authored help. However, quality control revealed that 32% of the initial responses of ChatGPT’s contained errors. The researchers applied a self-consistency technique—generating 10 responses per problem and selecting the most common answer—which dramatically reduced error rates to nearly 0% for algebra problems and 13% for statistics problems.

These results demonstrate that LLMs can be as effective as human-generated content for mathematics instruction, supporting our Avatar Tutor’s conversational AI approach.

[3] evaluated Rori, an AI-powered math tutor accessible via WhatsApp, involving approximately 500 students in Ghana. The conversational agent uses NLP and LLMs to deliver more than 500 micro-lessons with scaffolded practice questions. The results showed statistically significant higher math growth scores. This validates the effectiveness of chat-based AI tutoring in mathematics education, supporting our Avatar Tutor approach that employs conversational AI for mathematical instruction.

[7] presented an end-to-end evaluation of a Spoken Dialogue System to teach basic mathematics through play-based learning. The system deployed in real-world school settings enabled multimodal interactions including speech-based questions and manipulation of tangible objects. The study focused on improving Natural Language Understanding for interpreting mathematical intentions and provided insights into error propagation between AI components, demonstrating the practical viability of conversational AI systems for mathematics education.

[13] explore human-machine teaming paradigms within collaborative AR environments, investigating how virtual PA as Learning Companions can be integrated with human collaborators to facilitate social learning. Their study conducted three collaborative AR experiments with medical students learning to interview patients with stroke symptoms. The research demonstrates how learners can benefit from observing, interacting with and receiving feedback from both virtual pedagogical agents and human partners in AR settings, achieving significant results in self-efficacy and conceptual and procedural learning despite challenges in natural language processing technology. This work supports our Avatar Tutor approach, which similarly combines virtual pedagogical agents with immersive technology for educational enhancement.

[11] introduce Tutor CoPilot, a Human-AI approach providing real-time guidance to tutors. Their randomized controlled trial involving 900 tutors and 1,800 K-12 students found that students whose tutors had access to Tutor CoPilot were 4 percentage points more likely to master topics, with the greatest benefit for students of lower-rated tutors (9 percentage points improvement) and lower-experienced tutors (7 percentage points improvement). At \$20 per tutor annually, this demonstrates how Human-AI systems can effectively scale expertise.

3 System Design

Our conversational MR application represents the integration of multiple components of AI and immersive technology, designed to create seamless voice-driven mathematical learning experiences. The system architecture combines real-time voice processing, language modeling, and immersive visualization within a unified Unity-based framework running on the Meta Quest 3 platform.

The foundation of our conversational interface relies on Meta’s Wit.ai SDK, integrated through the Oculus platform, which provides voice recognition capabilities optimized for MR environments. This component handles both partial and full speech transcriptions, enabling real-time processing of student utterances as they interact with the Einstein avatar. The Wit.ai integration is particularly well-suited for our educational context, as it can effectively process mathematical terminology and commands while maintaining low latency essential for natural conversational flow. The system processes voice input through a multi-stage pipeline that begins with audio capture via the Quest 3’s built-in microphones, followed by real-time speech-to-text conversion through Wit.ai’s cloud-based recognition engine. This approach ensures high accuracy for mathematical vocabulary while providing the responsiveness necessary for interactive learning experiences.

At the core of our system’s intelligence lies Google’s Gemini API, specifically utilizing the gemini-2.5-flash-preview-04-17 model with function-calling capabilities enabled. This integration allows the Einstein avatar to not only engage in mathematical conversations, but also trigger specific Unity actions based on student requests. The function-calling feature is particularly crucial, as it enables translation between natural language commands and 3D mathematical visualizations. When students make requests such as “generate two intersecting planes” or “show me the RREF steps,” the Gemini model processes these utterances and determines the appropriate mathematical actions to execute. We have especially prompted our prompts in Gemini to provide feedback in a very specific structure that makes it easy to not only parse it out, but also call the appropriate functions in our code base for triggering the visualizations. The system also maintains a conversation history to provide coherent and contextual responses that build upon previous interactions.

For audio output, we employ ElevenLabs’ multilingual streaming Text-to-Speech (TTS) API, configured to generate responses in a distinctive voice profile designed for the Einstein avatar. The ElevenLabs integration streams audio directly to the Quest 3’s spatial audio system, enabling natural conversational timing and supporting the immersive learning environment. The streaming nature of TTS ensures that students receive immediate audio feedback, maintaining the natural flow of conversation essential for effective tutoring interac-

tions.

4 Conversational Learning Through the Einstein Avatar

Our application transforms abstract linear algebra instruction into engaging conversational experiences through the Einstein avatar, fundamentally changing how students interact with mathematical concepts. Rather than navigating complex interfaces or memorizing procedural steps, students engage in natural dialogue that mirrors authentic mathematical discourse, creating a more intuitive and pedagogically sound learning environment. The conversational interface enables students to request mathematical visualizations through natural language, with Einstein responding both visually and auditorily to reinforce conceptual understanding. When a student speaks the command “*draw me two planes that intersect on a line,*” Einstein immediately responds with engaging mathematical dialogue while simultaneously rendering the requested geometry.

Einstein’s response demonstrates sophisticated pedagogical awareness: “*Ah, a fascinating request! Imagine two pieces of paper cutting through the air; where they meet forms a line, doesn’t it? I can certainly generate two such planes for you. I’ll choose some values for their equations.*” This response exemplifies several key pedagogical principles: it connects abstract mathematical concepts to tangible real-world analogies (pieces of paper), validates the student’s mathematical curiosity, and provides transparency about the mathematical process being executed.

Figure 1 illustrates this interaction, showing both geometric visualization and Einstein’s conversational engagement. The parametric equation of the resulting line is displayed within the MR environment, allowing students to observe the mathematical relationship between the intersecting planes and their linear intersection.

Similarly, when students request more complex scenarios such as “*Generate three planes that intersect at a single point in 3D space*”, Einstein provides mathematically rich dialogue that contextualizes the visualization within broader mathematical understanding. His response—“*Ah, excellent! You wish to see how three planes can come together to meet at a single, unique point in space. Much like how three different paths can cross at one specific location. I shall generate three such planes for you now*”—demonstrates how conversational AI can scaffold learning by connecting abstract mathematical concepts to spatial intuition.

In Figure 2 a student likes to visualize the addition of vectors geometrically. The student asks “*Draw me two random vectors and then perform vector addition on it*”. Einstein responds back *Aha! Adding vectors, a fundamental*

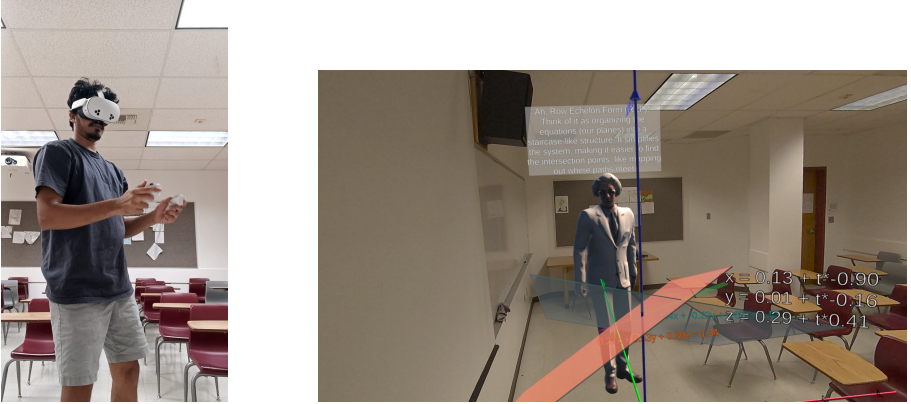


Figure 1: Left: Student with the Meta Quest 3 hardware in the classroom. Right: The Einstein avatar responds to a student's request to display two intersecting planes, providing both a geometric visualization and the parametric equation of their line of intersection. In this figure, the text above Einstein displays a transcript of his spoken response. Additionally, the figure captures the beginning of a step-by-step demonstration of the RREF algorithm, with Einstein's on-screen dialogue reflecting his explanation of the initial steps.

operation! We shall combine them, head to tail, to reveal their combined effect - the resultant vector. Let's engage the combining mode!

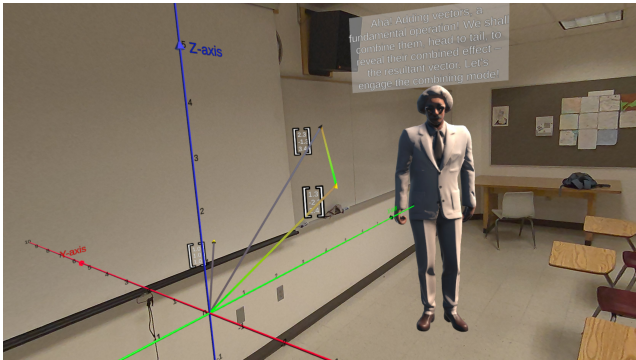


Figure 2: Vector addition where two random vectors are shown as column vectors in 3D space as $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$ and $\begin{bmatrix} 1.3 \\ -2.3 \\ 2.4 \end{bmatrix}$ and the resultant vector of $\begin{bmatrix} 2.3 \\ -1.3 \\ 3.4 \end{bmatrix}$

The application extends beyond basic geometric visualization to demonstrate real-world applications of linear transformations through an immersive Earth-Moon rotational system. This feature transforms abstract rotational matrices into tangible, observable phenomena that students can manipulate and control through voice commands and physical controllers.

Students can observe three distinct rotational transformations simultaneously: Earth’s rotation around its own axis, the Moon’s rotation around its own axis, and the Moon’s orbital motion around Earth. Each rotation is governed by its corresponding rotational matrix, allowing students to witness the direct mathematical relationship between matrix parameters and physical motion. Traditional linear algebra instruction often presents rotational matrices as abstract mathematical objects disconnected from their geometric meaning, creating a significant barrier to student understanding [1]. Our paper addresses that gap by providing concrete, embodied interactions with 3D transformations.

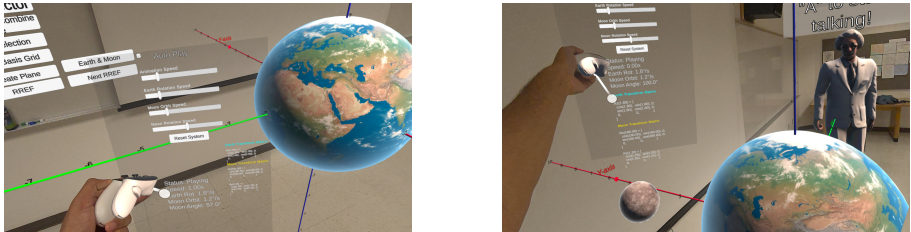


Figure 3: Earth-Moon rotational system illustrating linear transformations through astronomical visualization. Left: The three rotational matrices are displayed alongside controller options, with the Earth centered at the origin. Students can manipulate these matrices using voice commands or physical interaction. Right: The Moon orbits the Earth, and the user dynamically adjusts rotational parameters via the controller to observe the real-time effects of transformation.

The conversational interface enables intuitive control over these transformations through natural language commands such as “*increase the speed of the earth rotation*” or “*make the moon go slower around the earth.*” These voice interactions allow students to immediately observe how changes in rotational matrix parameters affect the corresponding physical motions, creating a direct connection between mathematical abstraction and observable phenomena.

The conversational approach offers several distinct advantages for applied linear algebra instruction in CS curricula. First, the natural language interface reduces cognitive load by eliminating the need to learn complex software interfaces, allowing students to focus entirely on mathematical concepts. This is

particularly valuable in CS education, where students often struggle with the transition from algorithmic thinking to mathematical abstraction.

Second, Einstein’s dialogical responses provide immediate conceptual scaffolding that connects mathematical operations to their geometric and physical interpretations. When students request specific visualizations, they receive not only the visual representation, but also the explanatory context that reinforces understanding. This conversational scaffolding is especially effective for CS students who benefit from understanding the practical applications of mathematical concepts in computational contexts.

Third, the real-time nature of the interactions enables iterative exploration and hypothesis testing. Students can quickly generate multiple geometric configurations, observe their properties, and develop an intuitive understanding through experimentation. This exploratory approach aligns with inquiry-based pedagogical methods while leveraging the unique capabilities of conversational AI and immersive visualization.

Finally, astronomical applications demonstrate the relevance of linear algebra concepts to computer graphics, game development, and simulation—core areas of CS where rotational transformations are fundamental. By observing how rotational matrices control planetary motion, students develop a deeper appreciation for the practical importance of linear algebra in computational applications, potentially increasing motivation and engagement in the subject matter. The integration of conversational AI with immersive visualization represents a significant advancement in mathematical pedagogy, offering CS students a more intuitive, engaging, and conceptually rich approach to linear algebra learning that bridges the gap between abstract mathematical theory and practical computational applications.

5 User Feedback and Planned Improvements

To evaluate the initial effectiveness and user experience of our conversational MR application, we conducted a pilot study with eight students who participated in a three-week linear algebra workshop designed for incoming students at California State University, Chico. These participants represented diverse academic backgrounds, including mathematics, chemistry, electrical and computer engineering, and arts, providing valuable insights into the application’s appeal across different STEM and non-STEM disciplines. The workshop focused on solving systems of linear equations, visualizing their geometric interpretations, and understanding the geometric RREF process.

The survey results, presented in Table 1, reveal consistently positive responses in all measured dimensions, with mean scores ranging from 3.625 to 4.375 on a 5-point Likert scale. The highest scores were fundamental visualiza-

tion capabilities (Q1: Mean = 4.375) and engagement with the Einstein avatar (Q3: Mean = 4.375), suggesting that both core technical functionality and the conversational interface effectively support learning objectives. The data indicates strong validation for our primary hypothesis that conversational MR enhances mathematical visualization. Question 1, addressing the core visualization of planes, lines and vectors, achieved the highest mean score with minimal variation (SD = 0.5175), indicating the broad consensus that the application effectively supports geometric understanding. Similarly, Question 5 (Mean = 4.25, SD = 0.7071) confirms that the 3D MR environment successfully builds intuition for spatial relationships fundamental to linear algebra.

In particular, Question 2 regarding linear transformations through the Earth-Moon system received the lowest mean score (3.625), though still indicating a positive reception. This result is particularly meaningful given that participants had not formally studied linear transformations at the time of trying the MR app, suggesting that the astronomical visualization approach successfully makes advanced concepts accessible to novice learners. The moderate standard deviation (0.7440) indicates some variation in how effectively different students connected rotational matrices to planetary motion, highlighting opportunities for improved scaffolding in future iterations.

The voice command system (Q4: Mean = 3.875, SD = 0.9910) showed the highest variability in responses, suggesting that while many students found voice interaction beneficial, some experienced difficulties that warrant technical improvements. This aligns with qualitative feedback indicating that voice recognition accuracy and system responsiveness require refinement for an optimal user experience. Student responses to the question about the interaction of the Einstein avatar reveal several key themes: The most prominent theme is enhanced engagement through personification of the learning experience. Students consistently noted that having a *“character to help explain”* and someone to *“tutor you while studying”* transformed the learning dynamic from passive absorption to active conversation. One student articulated this clearly: *“more interactive hands on activities are more engaging. And engagement leads to interest, and interest leads to learning.”* The responses also highlight the motivational impact of the expert persona. One student noted that the avatar *“can motivate the user to want to keep learning about this subject”* because *“he is an expert in that field.”* This suggests that the Einstein’s avatar successfully leverages aspirational learning, where students feel inspired by interacting with a renowned scientific figure. However, feedback also reveals important usability considerations. One student expressed preference for *“creating equations myself”* instead of relying on avatar generation, indicating that the balance between guided instruction and student agency requires careful calibration. This feedback suggests implementing more user control options while maintaining

the conversational benefits.

Although these preliminary results are encouraging, several limitations must be acknowledged. The small sample size ($n=8$) and non-randomized design limit generalizability, particularly for CS students who represent our primary target population. The diverse academic backgrounds of participants, while providing breadth, may not reflect the specific needs and prior knowledge of CS students taking applied linear algebra. Future evaluation plans include deployment with CS students during the applied linear algebra course, enabling comparison with traditional instruction methods through randomized controlled trials. This will allow measurement of learning outcomes beyond engagement and self-reported understanding, including performance on standardized assessments and retention of conceptual knowledge. Technical improvements based on user feedback will focus on enhancing voice recognition accuracy, particularly for mathematical terminology, and providing more granular user control over mathematical object creation. Additionally, the Earth-Moon visualization will be enhanced with more explicit connections to underlying rotational matrices to improve conceptual clarity for students without linear transformation background. The positive reception across diverse academic disciplines suggests broader applicability beyond CS education, though domain-specific adaptations may be necessary to optimize effectiveness for different student populations and mathematical concepts.

Question#	Statement	Mean	Std Dev	Max	Min
1	The app helped me better visualize and understand concepts such as planes, lines, and vectors in linear algebra.	4.375	0.5175	5	4
2	Even though I haven't formally studied linear transformations, the rotation of the moon around the Earth made intuitive sense to me.	3.625	0.7440	5	3
3	The ability to talk to Albert Einstein and have him show examples improved my interest in the topic.	4.375	0.7440	5	3
4	The voice command system made it easier to explore linear algebra visually.	3.875	0.9910	5	2
5	The 3D mixed reality environment helped me build an intuition for how planes and lines intersect.	4.25	0.7071	5	3
6	After using the app, I feel more motivated to learn the math behind what I saw.	4.00	0.7559	5	3
7	Having a virtual tutor like Albert Einstein made the learning experience more personal and engaging.	3.75	1.0351	5	2
8	Being able to talk to a virtual tutor directly will improve my ability to learn linear algebra concepts.	4.25	1.0351	5	2

Table 1: Survey results for the MR linear algebra app on Meta Quest 3. Participants rated each statement on a 5-point Likert scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree.

6 Conclusion

This work advances math education in computer science by combining conversational AI with MR to support linear algebra learning. Extending our prior

research on MR visualizations [4], we introduce a new paradigm where students interact naturally with a virtual Einstein avatar to request visualizations and receive immediate, pedagogically aware feedback. Our system integrates Meta Wit.ai, Google Gemini, and ElevenLabs within Unity, enabling seamless voice-driven interaction and immersive visualization. The Earth-Moon system exemplifies how familiar astronomical motion can ground abstract concepts like linear transformations in physical intuition—particularly relevant for computer science topics like graphics and machine learning. Preliminary feedback from eight users is promising, though larger studies are needed. Future work will expand to other linear algebra topics and improve error detection. By merging natural language interaction with MR, this research lays a foundation for AI-powered educational tools that make advanced math more accessible, engaging, and inclusive.

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