Exploring the Impact of Math-Iconic Gestures in a Virtual Reality Robotic Tutor

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Abstract

This pilot study explores the potential of embodied learning through robotic gestures in virtual reality (VR) for mathematics education. We investigated whether math-iconic gestures performed by a robotic tutor in VR (NICO) can enhance engagement and enjoyability when teaching percentage calculations. In a VR experiment with 26 university students (13 per condition), we compared a robotic tutor using math-iconic gestures versus one without these gestures. Results show participants in the gesture condition reported significantly higher levels of engagement (22.6% improvement, t(24) = 2.32, $p < 0.05$). The enjoyability scores were similar between conditions. Eye tracking data indicated increased visual attention to the robot in the gesture condition, with participants spending approximately 4.2 seconds longer looking at the robot's head and hands throughout the session. These findings suggest that embodied learning approaches utilizing gestures in VR robotic tutoring may offer promising pathways for mathematics education, particularly for enhancing student engagement.

1 Introduction

A famous story recounts a mathematical confrontation between encyclopedist Diderot and mathematician Euler at the court of Catherine the Great. As the tale goes, when atheist philosopher Diderot was entertaining the court, mathematician Euler approached him and declared, "Sir, $\frac{a+b^n}{n} = x$, therefore God exists. Reply!"Diderot, reportedly unable to understand the mathematical language, retreated in embarrassment. While historians doubt this encounter actually occurred (Gillings, 1954), the anecdote illuminates a profound truth: mathematics functions as a specialized language that can be as impenetrable as a foreign tongue without proper translation.

As the world becomes increasingly dependent on computation, mathematical formulations underpin more aspects of daily life. Research shows that math anxiety increases as more abstract concepts are introduced, disrupting cognitive resources essential for solving abstract mathematical problems (Lau a spol., 2022). The shift from conceptualizing learning as pure symbol processing to understanding it as an embodied phenomenon has significant implications for mathematics education (Lakoff a Núñez, 2000).

In human-human interactions, gestures serve as a natural intersection between embodied experience and abstract thought. Studies have demonstrated that teachers' use of gestures can facilitate student understanding in mathematics classroom settings (Alibali a spol., 2013). Alibali a spol. (2013) show that teachers spontaneously increase their use of gestures at points when students display lack of understanding, suggesting gestures play a crucial role in establishing shared understanding in mathematical discourse.

An important question is whether these benefits of gesture in human-human mathematical interactions translate to human-robot interaction or virtual environments. In the context of human-robot interaction, Michaelis a Di Canio (2022) investigated how robot gestures impact students' learning experiences with a physical NAO robot. They found that while learning outcomes did not significantly differ, students who interacted with a gesturing robot showed greater visual attention to the robot, were more likely to gesture themselves, and perceived the robot as a better social partner than students who interacted with a non-gesturing robot.

In a different approach using computer-generated avatars rather than physical robots, Cook a spol. (2017) found that children who viewed mathematics lessons from a virtual agent who gestured learned more effectively than children who viewed identical lessons without gesture. This suggests that even in virtual contexts, gestures can enhance mathematical learning.

Engagement serves as a critical predictor of mathematical achievement. Fung a spol. (2018) demonstrated this relationship in a large-scale study of 295,416 15-year-old students from 11,767 secondary schools in 34 countries who participated in PISA 2012. Their results showed that students who were more engaged had higher levels of academic achievement, regardless of other factors.

Robotic tutors offer several advantages for embodied mathematics learning, including endless patience and consistent demonstrations through gesture. Similarly, virtual reality provides another powerful medium for embodied learning experiences by allowing learners to manipulate abstract concepts in three-dimensional space, offering immediate visual feedback, and creating immersive environments where mathematical relationships can be physically explored (Chatain a spol., 2022).

Despite the promising potential of both robotics and VR for embodied learning, limited research has examined the specific impact of math-iconic gestures in VR robotic tutoring. While previous studies have investigated gestures in physical robots (Michaelis a Di Canio, 2022) or virtual agents (Cook a spol., 2017), the combination of math-specific gestures with a VR robotic tutor represents a novel approach that may uniquely enhance the learning experience. Furthermore, it remains unclear whether the benefits of gestures observed in human-human interactions translate effectively to human-robot interaction in virtual environments.

In this pilot study, we address this gap by investigating whether math-iconic gestures performed by a robotic tutor (NICO) in VR can enhance engagement and enjoyability when teaching percentage calculations. By measuring engagement, enjoyability, and visual attention through eye-tracking, we aim to provide initial evidence on the effectiveness of embodied mathematical representations in virtual robotic tutoring. Our findings contribute to understanding how embodied learning approaches using gestures in educational technology can be leveraged to make mathematics more accessible and engaging.

2 Methodology

2.1 Research Question and Hypothesis

Our study addressed the following research question: ”Do math-relevant gestures by a robotic tutor in VR improve engagement and enjoyability compared to a tutor without these gestures?”

We hypothesized that a robotic tutor that uses math-iconic gestures in VR will lead to higher engagement and more enjoyability.

2.2 Experimental Design

We employed a between-subjects design with two conditions: (1) Math- Iconic Gesture Condition: participants experienced math-iconic gestures in addition to basic deictic and social gestures, and (2) No Math-Iconic Gesture Condition: participants experienced only basic deictic (pointing) and social (waving) gestures. Both conditions included deictic gestures because pointing is essential for directing attention to specific mathematical elements, while social gestures like waving help establish rapport between the learner and robotic tutor.

2.3 Participants

Twenty-six participants (12 male, 14 female) with an average age of 21.9 years (range: 17-27) were recruited from the Faculty of Mathematics, Physics and Informatics at Comenius University. Participants were randomly assigned to either condition (n=13 each).

2.4 Experimental Setup and Procedure

The experiment took place in a VR laboratory using Unity. The NICO robot served as a virtual tutor with interactive elements. Each session lasted approximately 35-45 minutes, including:

1. Pre-test and initial questionnaire
2. VR interaction (approximately 15-20 minutes)
3. NASA-TLX (Hart, 2006) workload assessment
4. 3-minute break
5. Post-test and final questionnaire

In the gesture condition, the robot used specific math-iconic gestures:

- Halving gesture: One hand slicing a section in half
- Increase gesture: Gradual expansion of an area with both hands drifting outwards
- Decrease gesture: Gradual shrinking of an area with both hands drifting inwards

2.5 Assessment Instruments

To assess the impact of math-iconic gestures, measures were taken before the VR interaction, immediately after, and following a short cognitive rest period. Pre-intervention questionnaires were administered to collect demographic information and participants' prior experiences with virtual reality (VR) and robots. The GAToR scale was used to assess participants' general attitudes toward robots. We created a custom 10-item mathematics attitude questionnaire to measure participants' enjoyment, anxiety, and perceived importance of mathematics, as existing scales did not adequately fit our specific age group and context. A pre-test consisting of six percentage calculation problems established participants' initial performance levels prior to the intervention.

Immediately following the VR interaction, participants completed the NASA-TLX (Hart, 2006) to evaluate their cognitive and physical workload during the experience. After a mandatory 3-minute break, participants then took a post-test, which included six percentage calculation problems of equivalent difficulty to those in the pre-test.

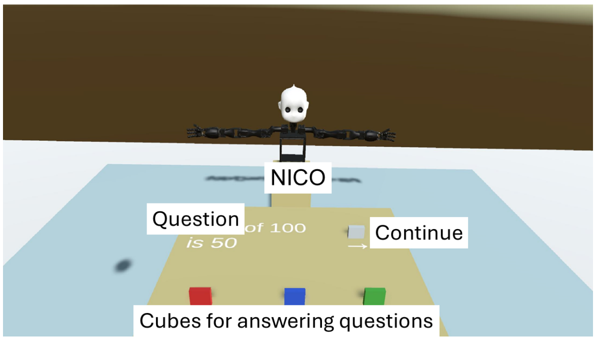
The final post-intervention assessment measured key aspects of the learning experience. From the Intrinsic Motivation Inventory (Deci a Ryan, 2000), we used the Interest/Enjoyment and Value/Usefulness subscales. From the User Engagement Scale (O'Brien a spol., 2018), we used the Perceived Usability and Focused Attention subscales.

Additionally, we developed a custom 8-item Robot Perception scale to evaluate the robot's perceived effectiveness and trustworthiness. For the gesture condition, we included a 5-item scale to assess the noticeability and usefulness of gestures.

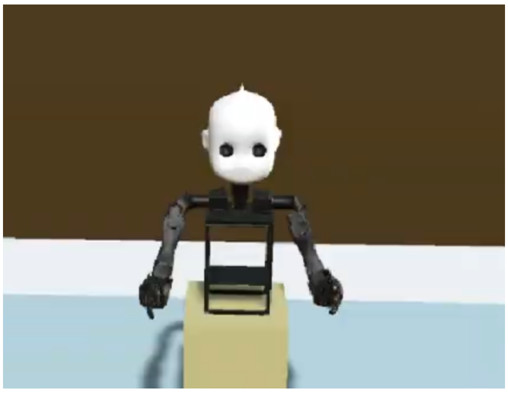
All questionnaire items utilized 5-point Likert scales ranging from "Strongly disagree"to "Strongly agree."

2.6 Eye-tracking

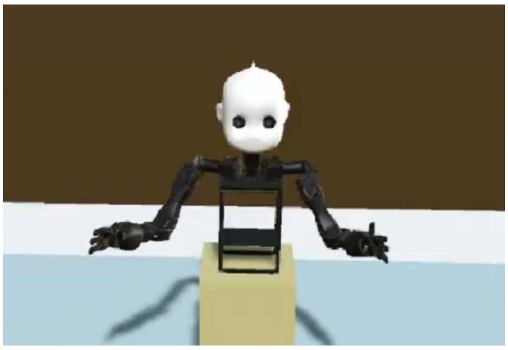
The VR headset was equipped with Tobii eye-tracking technology. Seven objects of interest were defined: the NICO robot's head, hands, and four interactive cubes. Fixation duration on each object was recorded to measure visual attention.



Obr. 1: VR Setup with NICO robot and interaction cubes.



Obr. 2: Math-iconic gesture for "increase" - starting position.



Obr. 3: Math-iconic gesture for "increase" - ending position with expanded area.

3 Results

3.1 Statistical Analysis

For each measure, we calculated individual participant scores, then computed group means and standard deviations for both conditions. Independent samples t-tests were conducted to determine statistical significance with a threshold of $p < 0.05$. We also calculated the percentage difference between conditions to examine the practical significance of our findings.

3.2 Engagement and Enjoyment

Participants in the gesture condition reported significantly higher levels of engagement compared to those in the no-gesture condition, while enjoyment levels were similar between the two groups:

- Engagement: With gestures (M = 3.52, SD = 0.81) vs. Without gestures (M = 2.87, SD = 0.64), representing a 22.6% improvement (t(24) = 2.32, $p < 0.05$)
- Enjoyment: With gestures (M = 3.68, SD = 0.85) vs. Without gestures (M = 3.72, SD = 0.63), showing no significant difference between conditions (t(24) = -0.14, $p > 0.05$)

3.3 Robot Perception and Usability

Analysis of the Robot Perception scale showed a trend toward more positive robot perception in the gesture condition (M = 3.81, SD = 0.73) vs. without gestures (M = 3.54, SD = 0.65), representing a 7.6% improvement, though not statistically significant (t(24) = 1.02, $p > 0.05$).

Usability scores were nearly identical between conditions (Gesture: M = 3.79, SD = 0.65; No-gesture: M = 3.81, SD = 0.59), with no significant difference (t(24) = -0.08, $p > 0.05$). This indicates that the addition of gestures did not complicate the interaction with the virtual tutor.

Mental demand as measured by NASA-TLX showed no significant difference between conditions (Gesture: M = 2.08, SD = 0.86; No-gesture: M = 2.15, SD = 0.69; t(24) = -0.25, $p > 0.05$), indicating that the addition of gestures did not increase cognitive load.

3.4 Eye-tracking Results

Eye-tracking data revealed that participants in the gesture condition spent more time looking at the robot's head and hands compared to those in the no-gesture condition. On average, participants in the gesture condition spent approximately 4.2 seconds longer looking at the robot's head and hands throughout the session.

3.5 Qualitative Feedback

Interview responses revealed several themes about the math-iconic gestures. Many participants felt these gestures would benefit younger learners, with one noting they "help children understand complicated concepts, engages them more than just verbal explanation." Another mentioned gestures would "help students to learn and also revise how to calculate percentages."

Participants' reactions varied widely. Some found the gestures "helpful and recognized as math relevant" while others considered them "slow and not useful, distracting." This suggests important individual differences in how people process embodied information. One participant appreciated how gestures "help to guide the calculations in head and engage the attention in a different way than a normal math class."

Interestingly, several participants in the no-gesture condition expressed that something was missing from their experience. One "wished for gestures" and found the "voice monotonous" without physical expressions. In the questionnaire, participants often described the gesture-enabled robot as "more human-like" and feeling "more like a teaching assistant than a passive program."

Several participants explicitly mentioned motivational aspects, writing that gestures could "encourage more people to learn math and enjoy solving math problems" and "increase the focus and interest in children to learn" - observations that align with our quantitative finding of significantly improved engagement.

4 Discussion

Our findings suggest that math-iconic gestures performed by a robotic tutor in VR can significantly enhance engagement in mathematics learning. The 22.6% improvement in engagement is particularly noteworthy given that engagement is a key predictor of mathematical achievement (Fung a spol., 2018). However, we did not observe a significant difference in enjoyability between conditions, suggesting that gestures primarily function as cognitive tools rather than hedonic enhancers of the learning experience.

The eye-tracking data provides additional support for the engagement effect, with participants in the gesture condition spending more time looking at the robot. This increased visual attention may reflect greater interest and focus on the robot's embodied representations of mathematical concepts.

5 Future Research Directions

This pilot study opens several promising directions for future research. Testing with the intended audience of 5th-grade children would provide more relevant insights about the educational potential of this approach. Additionally, exploring applications for neurodiverse populations could reveal how embodied learning through VR might benefit learners with different cognitive profiles. Future work should also focus on developing math-iconic gestures for more complex mathematical concepts beyond basic percentages. Finally, comparing VR robotic tutoring with physical robots would provide valuable insights into the role of embodiment in educational technology.

6 Conclusion

This investigation into math-iconic gestures in VR robotic tutoring suggests that embodied approaches to mathematics education hold promise, particularly for enhancing student engagement. Our findings indicate that math-iconic gestures can significantly improve how absorbed learners become in mathematical content, even when enjoyability remains unchanged. The combination of robotics, virtual reality, and gesture-based instruction creates new possibilities for making mathematics more accessible through embodied learning experiences.

The diverse responses to gestures in our qualitative data suggest that adaptable communication styles in educational technology—allowing users to customize the level of gestural information—may be optimal for accommodating diverse learning preferences. Future educational technologies might benefit from incorporating these insights to create more effective and personalized learning environments.

Acknowledgments

This research was conducted as part of the MEi:CogSci Mobility Project at Comenius University in Bratislava. We thank all participants for their time and valuable feedback. Special thanks to RNDr. Kristína Malinovská, PhD for her supervision.

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